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A solar cavity-receiver packed with an array of thermoelectric converter modules

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Abstract

We report on the design of a solar cavity-receiver packed with an array of thermoelectric converter (TEC) modules, which enables efficient capture of concentrated solar radiation entering through a small aperture. A 1 kW demonstrator (proof-of-concept) containing 18 TEC modules, each consisting of Al_2O_3 absorber/cooler plates, and *p*-type $La_{1.98}Sr_{0.02}CuO_4$ and *n*-type $CaMn_{0.98}Nb_{0.02}O_3$ thermoelements, was subjected to peak solar concentration ratios exceeding 600 suns over its aperture. The TEC modules were operated at 900 K on the hot side and 300 K on the cold side. The measured solar-to-electrical energy conversion efficiency was twice that of a directly irradiated TEC module. A heat transfer model was formulated to simulate the solar cavity-receiver system and experimentally validated in terms of open-circuit voltages measured as a function of the mean solar concentration ratio. Vis-à-vis a directly irradiated TEC module, the cavity configuration enabled a reduction of the re-radiation losses from 60% to 4% of the solar radiative power input. Theoretical considerations for TEC with figure-of-merit higher than 1 indicate the potential of reaching solar-to-electrical energy conversion efficiencies exceeding 11%.

Keywords: Thermoelectric converter; Concentrated solar energy; Heat transfer; Radiation; Cavity; Receiver

1. Introduction

A thermoelectric converter (TEC) comprises *p*-type and *n*-type semiconductor legs sandwiched between two ceramic hot/cold plates and connected thermally in parallel and electrically in series (Goldschmid and Nolas, 2001; Min, 2006; Rowe, 2006). The temperature gradient across the legs induces a voltage due to the Seebeck effect. The TEC performance is characterized by its figure-of-merit, $ZT = S^2T/(\rho\kappa)$. However, due to the relatively low heat-to-electricity conversion efficiencies for $ZT \leqslant 1$ of ceramic materials, TECs have not yet found widespread applications at high temperatures (Riffat and Ma, 2003). With the advent of novel functional ceramic materials, high-temperature thermal reservoirs are being considered, e.g. concentrated solar energy (Naito et al., 1996; Tomeš et al., 2008; Weidenkaff et al., 2008). The design of a solar cavity-receiver for supplying high-temperature heat to a thermionic/thermoelectric system has been proposed and temperature distributions were measured on a prototype made of graphite (Naito et al., 1996). The direct conversion of concentrated solar radiation into electricity at high temperatures has been recently experimentally demonstrated (Tomeš et al., 2008, 2010). A heat transfer analysis of directly-irradiated single TEC modules has shown that

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Nomenclature

A	surface, m^2
a	aperture width, m
b	plate thickness, m
$\tilde{C}$	solar concentration ratio
d	distance between legs, m
e	charge of electron / charged particles, Coul
F_{k-j}	view factor from surface k to j
h	heat transfer coefficient, W m^{-2} K^{-1}
I	solar irradiation, W m^{-2}
j	current density, A m^{-2}
l	leg length, m
L	length of cavity-receiver, m
k	thermal conductivity, W m^{-1} K^{-1}
M	number of p/n-type leg pairs
N	number of modules
P	electric power output, W
p	plate length, m
q''	heat flux, W m^{-2}
Q_{solar}	solar radiative power input, W
S	Seebeck coefficient, V K^{-1}
T	temperature, K
W	width of cavity-receiver, m
w	width of legs, m
V	voltage, V

Greek letters

α	absorptivity
$\alpha_{apparent}$	apparent absorptance
γ	iteration step
δ_{kj}	Kronecker delta
ε	total emissivity, error
η	solar-to-electricity efficiency
μ	chemical potential, J mol^{-1}
ρ	electrical resistivity, Ω m
σ	Stephan–Boltzmann constant, W m^{-2} K^{-4}

Subscripts

c	cold
h	hot
i, j	finite volume indices
m	middle
OC	open-circuit
∞	surroundings

Dimensionless group

Nu	Nusselt number
Ra	Rayleigh number
ZT	Figure-of-Merit

Abbreviations

CPC	compound parabolic concentrator
DNI	direct normal irradiation
HFSS	high flux solar simulator
MC	Monte Carlo
TEC	thermoelectric converters

60% of the incident solar radiation is lost by re-radiation (Suter et al., 2010).

In this paper, a solar cavity-receiver is packed with TEC modules that are directly exposed to concentrated solar radiation. As it will be shown in the analysis that follows, the advantages of the proposed design are two-folded: (1) the geometrical configuration allows for efficient capture of concentrated solar radiation and significant reduction of the re-radiation losses; (2) the direct irradiation of the TEC modules allows efficient heat transfer to the site, bypassing the limitations associated with conduction heat transfer through the walls of an opaque solar absorber (i.e. limitations imposed by the materials with regards to maximum operating temperature, thermal conductivity, and resistance to thermal shocks). A 1 kW demonstrator is fabricated as a proof-of-concept of the proposed configuration. A heat transfer model is formulated and validated in terms of open-circuit voltages measured as a function of the mean concentration ratio over the aperture, and further applied to analyze the thermal energy partition. In this study, no attempt was undertaken to optimize the materials of the TEC modules for improving their Figure-of-Merit.

2. Heat transfer model

The solar cavity-receiver configuration is shown schematically in Fig. 1. It consists of a rectangular parallelepiped (box) with a windowless rectangular aperture for the access of concentrated solar irradiation. Because of multiple internal reflections, the cavity's apparent absorptance[1] $\alpha_{apparent}$ exceeds the inner surface absorptivity α and, consequently, increases its ability to absorb incoming irradiation. $\alpha_{apparent}$ has been calculated for cylindrical, conical, and spherical geometries having diffusely and specularly reflecting inner walls (Lin and Sparrow, 1965; Steinfeld, 1991; Siegel and Howell, 2002). Smaller apertures reduce re-radiation losses but intercept less sunlight. Consequently, the optimum aperture size becomes a compromise between maximizing radiation capture and minimizing radiation losses (Steinfeld and Schubnell, 1993). To some extent, the aperture size may be reduced with the help of non-imaging secondary concentrators, e.g. compound par-

[1] Fraction of energy flux emitted by a blackbody surface stretched across the aperture that is absorbed by the cavity walls.