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Performance evaluation and parametric optimum design of a thermoelectric refrigerator driven by a dye-sensitized solar cell

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ABSTRACT

A novel model of the hybrid device based on an integration of both the dye-sensitized solar cell (DSSC) and the semiconductor thermoelectric refrigerator (TER) is developed to harvest solar energy for refrigeration. In the investigation, an electron diffusion model is used to determine the current voltage characteristics of the DSSC. The coefficient of performance (COP) of the hybrid system is derived. The effects of the current density and film thickness of the DSSC, the external and internal irreversibilities of the TER, and the structure parameter of the hybrid system on the performance are discussed in detail. In the parametric design, the optimal values of the current density, film thickness, and structure parameter are about $11.7\ Acm^{-2}$, $5.62\ \mu m$, and $0.000465\ cm^{-1}$, respectively. The results show that these parameters can be optimally designed to obtain a maximum COP of the refrigeration system.

Evaluation de la performance et conception optimale paramétrique d'un réfrigérateur thermoélectrique entrainé par une cellule solaire à colorant

Mots clés : Cellule solaire à colorant ; Réfrigérateur à semi-conducteur thermoélectrique ; Dispositif hybride ; Coefficient de performance ; Conception optimale

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Abbreviations: DSSC, dye-sensitized solar cell; TER, thermoelectric refrigerator; TCO, transparent conducting oxide; COP, coefficient of performance

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Nomenclature

$a_{h/c}$	thermal conductance ratio
A	effective area (cm)
d	thin film thickness (μm)
c	structure parameter of the hybrid system (μm)
D	electron diffusion length ($cm^2\,s^{-1}$)
G	solar spectrum intensity ($mW\,cm^{-2}$)
I	current of the TER ($mA\,cm^{-2}$)
J_D	current density of the DSSC ($mA\,cm^{-2}$)
k	thermal conductivity ($mW\,cm^{-1}\,K^{-1}$)
K	thermal conductance ($mW\,K^{-1}$)
k_B	Boltzmann constant (JK^{-1})
l	electron diffusion length (cm)
L	length of thermoelectric arms (cm)
m	ideality factor
$n(x)$	excessive electron concentration (cm^{-3})
N	couple number of the TER
n_0	electron concentration under a dark condition (cm^{-3})
P_D	power output of the DSSC (mW)
P_T	the power input of the TER
q	electron charge (C)
Q_c	heat absorbed from cooled space (*mW*)
Q_h	heat released to the heat sink (mW)
R	electric resistance (*Ωcm*)
S	Seebeck coefficient (VK^{-1})
$T_{h/c}$	temperature of the heat sink/cooled space (K)
$T_{hj/cj}$	temperatures of the hot/the cold junctions of the TER (K)
T	temperature (K)
T_R	temperature of the DSSC (K)
$U_{h/c}$	overall heat-transfer coefficients of the heat exchangers at the cold/hot sides ($mW/K^{-1}\,cm^{-2}$)
V_D	external voltage of the DSSC (V)
x	coordinate measured from the TiO_2/TCO interface (μm)
Z	figure of merit (K^{-1})

Greek symbols

α	light absorption coefficient (cm^{-1})
ε	the COP of the hybrid system
ε_T	the COP of the TER
η_D	efficiency of the DSSC
ρ	electrical resistivity (Ωcm)
τ	electron lifetime (ms)
Φ	incident irradiation intensity ($cm^{-2}\,s^{-1}$)

Superscripts and subscripts

0	parameter of a n/p junction couple
D	dye-sensitized solar cell
h/c	heat sink/cooled space
n/p	n-/p- type semiconductor leg
opt	optimal value
SC	short-circuit current density
T	thermoelectric generator

1. Introduction

The need for air-conditioning in buildings and for industrial cooling is growing rapidly worldwide. The use of solar energy to power refrigerator will provide a new promising approach to meet this increasing demand. Compared with conventional vapor compression refrigeration, solar refrigeration is a promising technology, given the fact that it is more compact, silent, and indispensable (Al-Ugla et al., 2015; Khaliq, 2015). Solar refrigeration system is also environment-friendly because it does not use ozone-depleting chlorofluorocarbons nor greenhouse gases (Allouhi et al., 2015; Bortolini et al., 2015; Dennis et al., 2015). A solar refrigeration system can convert a part of solar energy into electrical energy and power a vapor compression unit to realize refrigeration (Sarbu and Sebarchievici, 2013). Otanicar et al. concluded that the continuous growth of the coefficient of performance (COP) of vapor compression refrigerator and strong cost reduction targets for photovoltaic technology will greatly reduce the capital investment of traditional solar refrigeration in the near future (Otanicar et al., 2012).

Solar refrigeration will become one of the important room-temperature refrigeration technologies and it can be realized in various ways, covering solar electric, solar thermal, and some new emerging technologies. A solar electric refrigeration system consists mainly of photovoltaic cells and an electrical refrigeration device, where solar energy is converted into electrical energy and used for refrigeration (Anand et al., 2015; He et al., 2013; Kim and Infante Ferreira, 2008). Solar thermal systems utilize solar heat rather than solar electricity to obtain refrigeration effect, including thermo-mechanical, absorption, adsorption, and desiccant solutions (El Fadar, 2015; Said et al., 2015). The present study will focus on a solar electric refrigeration system.

For a solar electric refrigeration system, the output of solar cells is typically of direct current electricity, whereas most domestic and industrial electrical appliances use alternating current. Therefore, a complete traditional solar cell powered vapor compression refrigeration system requires an extra inverter circuit, making the system complex (Byrne et al., 2015; Fong et al., 2010). Solar thermoelectric cooling is a new idea on the basis of the possibility of using solar electricity to drive a thermoelectric cooler (Liu et al., 2015). Thermoelectric cooler is a new type of solid-state device for refrigeration utilizing the Peltier effect (Ma and Yu, 2014). It offers the advantages of quiet operation, compact size, high reliability, and exact temperature control, and thus has the potential to be used in many applications including aerospace, military, industrial, and commercial areas (Gasik and Bilotsky, 2014).

Dai et al. derived a thermoelectric refrigerator driven by solar cells and demonstrated that the unit can maintain the temperature in the refrigerator at 5–10 °C (Dai et al., 2003a, 2003b). Abdul-Wahab et al. fabricated a portable solar thermoelectric refrigerator unit and the experiment results showed that the