Applied Energy 113 (2014) 924–931

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Experimental and theoretical analysis of cell module output performance for a thermophotovoltaic system

Xiaojie Xu [a], Hong Ye [b], Yexin Xu [a], Mingrong Shen [a,*], Xiaojing Zhang [a], Xi Wu [a,*]

[a] School of Physics Science and Technology, Soochow University, Suzhou, Jiangsu 215006, PR China
[b] Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei, Anhui 230027, PR China

HIGHLIGHTS

- An accurate theoretical model for thermophotovoltaic system is constructed.
- Parallel connected module is superior if radiator temperature is uneven.
- Series connected module is superior if cell temperature is uneven.
- Short circuit current of series module rises when the shunt resistance decreases.
- Fill factor is not always accurate to evaluate the module performance.

ARTICLE INFO

Article history:
Received 22 May 2013
Received in revised form 23 July 2013
Accepted 9 August 2013
Available online 11 September 2013

Keywords:
Thermophotovoltaic module
Output performance
Network efficiency
Fill factor

ABSTRACT

An experimental thermophotovoltaic (TPV) system with a cylindrical-geometry radiator was established to test the output performances of modules under different conditions. The results demonstrate that the output performance of a cell module decreases when the combustion power increases because of the uneven temperature of the radiator or cells. On this basis, a theoretical model for a TPV system was constructed to compare the performance under different conditions of the series-connected (SC) module and the parallel-connected (PC) module, and was verified by the experimental results. The influences of the temperature gradient of the radiator or the cell module, and the series and shunt resistance of the TPV cell on the module performance were analyzed in detail. The results demonstrate that the PC module can effectively reduce the mismatch loss of output power caused by the uneven radiator temperature. The PC module, for instance, has a maximum output power of 2.54 times higher than that of the SC module when the radiator temperature difference is 500 K. However, the output performance of the module connected in series is superior to the PC module while the cell temperature is non-uniform. The output power of the SC module is 9.93% higher than that of the PC module at the cell temperature difference of 125 K. The short circuit current of the SC module is sensitive to the series and shunt resistance if the radiator temperature distribution is non-uniform. As the shunt resistance falls from ∞ to 0.5 Ω, the current varies from 1.757 A to 4.488 A when the radiator temperature difference is 500 K. As the series resistance rises from 6.6 mΩ to 0.5 Ω, this current falls from 2.132 A to 1.654 A under the same condition. This research also shows that the fill factor is not appropriate to evaluate the output performance of a TPV system. Furthermore, the theoretical model developed in this study is used to analyze and optimize the experimental TPV system, and consequently the output powers under two different conditions are enhanced by 20.24% and 33.99% respectively when a module is connected in parallel.

1. Introduction

Thermophotovoltaic (TPV) systems have great potential application in commerce, military and aerospace industry. At present, the research on TPV primarily focuses on the spectral control technology and system construction [1–6]. In 2008, Tobler and Durisch produced selective radiators by vacuum plasma-spray coating of erbium doped garnet $Er_{1.5}Y_{1.5}Al_5O_{12}$and Er_2O_3 on the intermetallic alloy $MoSi_2$. The radiators were fully operable in an oxygen-containing atmosphere at a temperature of 1600 °C, were highly thermal-shock stable, and showed good selective-emitting properties [7]. In 2010, Mao and Ye modified the one-dimensional Si/SiO_2 photonic crystals with large oscillations

* Corresponding authors. Tel./fax: +86 512 65112066 (M. Shen), tel.: +86 512 65112605 (X. Wu).

E-mail addresses: mrshen@suda.edu.cn (M. Shen), wuxi@suda.edu.cn (X. Wu).

0306-2619/$ - see front matter Crown Copyright © 2013 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.08.029

Nomenclature

A_c	cell active area (m^2)
c	light velocity (m/s)
h	Planck constant
I_0	reverse saturation current (A)
I_{ph}	photo-generated current (A)
k	Boltzmann constant
m	number of the cells
n	cell quality factor
$P_{act,cell\text{-}x}$	actual output power of the xth cell in the module (W)
$P_{max,cell\text{-}x}$	maximum output power of the xth cell (W)
$P_{max,module}$	maximum output power of the module (W)
q	quantity of the electricity of electron (c)
$q_i(\lambda)$	spectral irradiation density projected onto the cell surface (W/m^2)
Q_{chem}	chemical energy of C_3H_8 (kW)
R_s	series resistance (Ω)
R_{sh}	shunt resistance (Ω)
T_c	cell temperature (K)
λ	wavelength (μm)
λ_g	bandgap wavelength (μm)
$\eta_Q(\lambda)$	external quantum efficiency
η_{net}	network efficiency of the module

Acronyms

TPV	thermophotovoltaic
SC	series-connected
PC	parallel-connected

around 1.45–1.75 μm in the pass band. The improvement of the TPV system performance by utilizing the modified photonic crystals filter was then predicted. The results indicated that the spectral efficiency and the power density increased 21.0–5.9% and 14.8–5.3% at 1200–1800 K radiator temperature compared with the original photonic crystals [8]. In 2012, Qiu and Hayden built a novel cascading thermophotovoltaic and thermoelectric power generation system. The output power and the efficiency of the TPV system with GaSb cells were 123.5 W and 1.49%, respectively, and the efficiency of the whole system was 5.2% [9]. Although there are a number of theoretical and experimental researches on TPV systems, most of them concentrate on the influences of the types of radiators and TPV cells or filter parameters on the system performance. *I–V* characteristics of a photovoltaic cell are affected by the cell parameters, the light intensity and the cell temperature. Much work has been reported in the field of photovoltaics about these factors [10,11]. However, further research should be done to verify whether these conclusions are applicable to TPV systems which are usually exposed to a high radiation heat flux. Unfortunately, it is rarely reported. In 2004, Baldasaro et al. discussed the influence of the breakdown voltage on *I–V* characteristics of a TPV cell. It was found that there was no change in the maximum electric power output when the reverse breakdown voltage dropped. However, the fill factor of the module decreased rapidly because of the obviously increase of the short circuit current [12].

In 2011, the authors established an experimental TPV system with a planar SiC radiator. Additionally, a mathematical physical model was constructed to analyze the influences of the radiator and cell temperature on the output performance of a single TPV cell. However, the performance of the module was only experimentally analyzed [13]. The main reason is that the theoretical model of the TPV module is so complicated that the module performance is not simply a linear superposition. There are a lot of reasons for the complexity of the theoretical model; one of the most important factors is the structure of the radiator. Due to the cavity effect, the cylindrical radiator is more conducive to achieving a high output power density than the planar one [14]. Therefore, an experimental TPV system with a cylindrical-geometry radiator was established in this study to test the output performances of modules under different conditions. A mathematical physical model was constructed to analyze the influences on the module performance of the factors such as cell connection configurations, cell parameters, the radiator or cell temperature difference. On this basis, the experimental TPV system was analyzed and optimized.

2. Experimental system

As shown in Fig. 1, the experimental system is made up of a combustor, a cylindrical SiC radiator with an inner combustion tube, TPV cell modules, a cooling device and a monitor and testing unit. The length of the SiC radiator is 754 mm. Its external diameter and wall thickness are 66 mm and 6 mm, respectively. The length, external diameter and wall thickness of the inner combustion tube are 734 mm, 66 mm and 6 mm, respectively. When the mixture of C_3H_8 and air is burned, the combustion flue gas and the flame spread along the inner tube and then the flue gas is reflected by the spherical closed end into the space between the radiator and the inner tube. The combustion energy is used to heat the SiC radiator. The exhaust flows out of the chimney. Six aluminum hydrocoolers with the length of 200 mm are equipped outside of the high-temperature radiator. A module consisting of 56 (14 × 4) GaSb cells is placed on the inner surface of every hydrocooler to generate electric power using the radiant energy from the high-temperature radiator. The minimum distance between the radiator and the cells is 1.95 cm. The module is connected to variable loads to obtain *I–V* characteristics by four-probe method under different experimental conditions. The outer surface of the radiator exposed to the environment was wrapped with insulation asbestos to reduce energy loss, as shown in Fig. 2. Five equi-distant holes with the deep of 0.8 mm are drilled on the surface of the radiator. B-type thermocouples with an accuracy of ±0.25%t are buried in the holes and are fixed by the ultrahigh temperature plastic which can withstand a high temperature of 1730 °C to measure the temperatures of the radiator (measuring point 1–5). K-type thermocouples with an accuracy of ±0.75%t are employed to measure the temperature

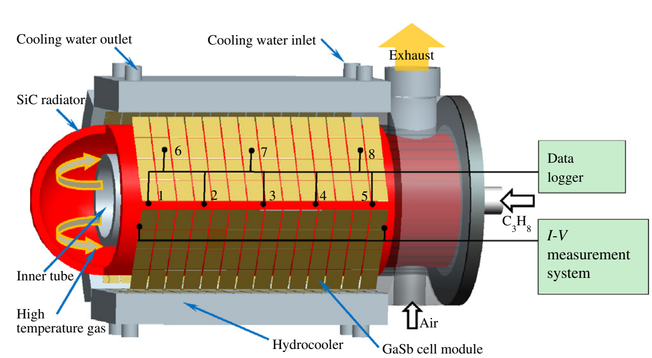

Fig. 1. Schematic of the TPV experimental system.