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A combined thermophotovoltaic-thermoelectric energy converter

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ABSTRACT

The performance of a combined thermoelectric (TE) and thermophotovoltaic (TPV) energy converter was theoretically modeled. The thermal input power to the system is determined by the TPV input high temperature. However, TE converters operate at lower input temperatures. Therefore, a thermal conduction block must be used to reduce the high input temperature to the lower TE operating temperature. The TE portion of the system was analyzed using a one dimensional conduction model. A radiation transfer model was used for the TPV portion of the system. There are two significant results. First, the combined system has a larger efficiency than TE or TPV alone in a narrow temperature range. This temperature range lies between typical TE operating temperatures ($\approx$ 600 K) and TPV operating temperatures ($\approx$ 1200 K). Second, the electrical power output in this temperature range is significantly greater than TE or TPV alone.

1. Introduction

Thermophotovoltaic (TPV) (Chubb, 2007; Bauer, 2011) and thermoelectric (TE) (Decker, 1997; Angrist, 1976) are two energy conversion concepts that are well-known. Both concepts are direct thermal to electric energy converters that require no moving parts. Therefore, reliability and long lifetime are characteristics of these concepts. Thermoelectrics is an older concept and has shown extremely long lifetime. It has operated for tens of years powering deep space probes.

TPV utilizes thermally generated photons to produce electric currents in photovoltaic (PV) cells. TE utilizes thermally generated electrons and holes in a semiconductor to produce electric currents. TPV has been proposed for space power systems (Crowley et al., 2005), automotive applications (Mazzer et al., 2000), and residential applications (Fraas, 2014). Thermeolectrics has similar applications (Wang et al., 2013; El-Genk et al., 2003; Ohara et al., 2015). A review of the latest TE materials is given by Zhang and Zhao (2015).

A schematic drawing of the proposed system is shown in Fig. 1. All parts of the system are in a vacuum. The TPV part of the system consists of a photon emitter at temperature T_E, an optical cavity and a PV array. The TE portion of the system consists of a conduction block, and a TE module that has an input operating temperature T_2. The conduction block serves two purposes. First, it lowers the emitter high temperature ($\approx$ 1200 K) to the TE operating temperature T_2 ($\approx$600 K). Second, it provides a nearly uniform temperature T_2 across the TE module.

In a TPV system a major loss is the radiation that leaks out at the edges of the optical cavity (Chubb, 2007, Ch. 7 and 8). To prevent this loss edge shields are used to block the radiation. However, these shields introduce a heat conduction path between the emitter and the sink. To make this conduction loss as small as possible very thin radiation shields are used. Introducing the conduction block and TE module provides the radiation shield but eliminates the conduction loss. The efficiency of the combined system is the following.

$$\eta_T = \frac{P_{TPV} + P_{TE}}{Q_{in}} \tag{1}$$

where P_{TPV} and P_{TE} are the electrical power outputs of the TPV converter and TE converter respectively and Q_{in} is the total thermal power input to the system. Individual efficiencies of the TPV and TE parts of the system are the following.

$$\eta_{TPV} = \frac{P_{TPV}}{Q_{TPV}(T_E)} \tag{2a}$$

$$\eta_{TE} = \frac{P_{TE}}{Q_{TE}(T_2)} \tag{2b}$$

where

$$Q_{in} = Q_{TPV}(T_E) + Q_{TE}(T_2) + Q_{loss} \tag{2c}$$

and Q_{loss} is the heat loss from the conduction block. Combining Eqs. (2) and (1) results in the following.

$$\eta_T = \frac{\eta_{TPV} Q_{TPV}(T_E) + \eta_{TE} Q_{TE}(T_2)}{Q_{TPV}(T_E) + Q_{TE}(T_2) + Q_{loss}} \tag{3}$$

The $\eta_{TE} Q_{TE}(T_2)$ term is constant since T_2 is fixed at the maximum

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List of symbols

Parameter	Definition
T_E	emitter temperature, K
τ	width of conduction block at emitter, cm
L	length and width of emitter, cm
d_e	depth of optical cavity, cm
d	length of conduction block, cm
w	width of conduction block at TE module, cm
T_2	input temperature to TE module, K
q_{in}	input heat flux to TE module, W/cm^2
q_{r1}	radiation flux leaving conduction block into the optical cavity, W/cm^2
q_{r2}	radiation flux leaving conduction block into the sink, W/cm^2
q_{L2}	radiation flux leaving conduction block into radiation shields, W/cm^2
$\rho(\lambda)$	spectral reflectance
$\epsilon(\lambda)$	spectral emittance
$e_b(\lambda,T)$	blackbody spectral emissive power, W/cm^2 μm

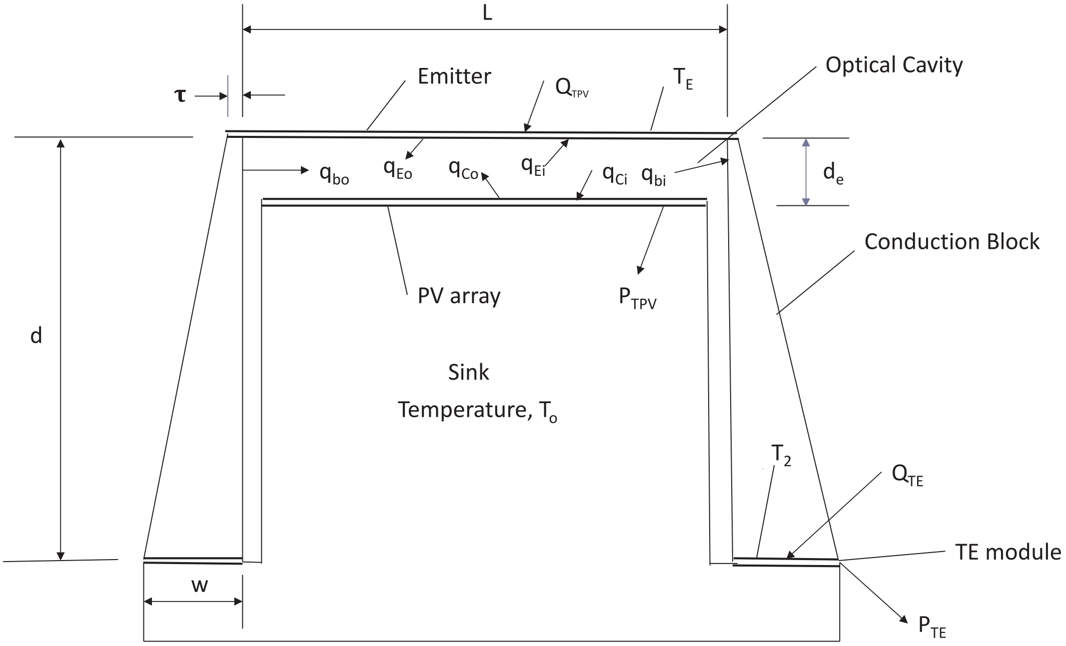

Fig. 1. Schematic of TPV + TE system.

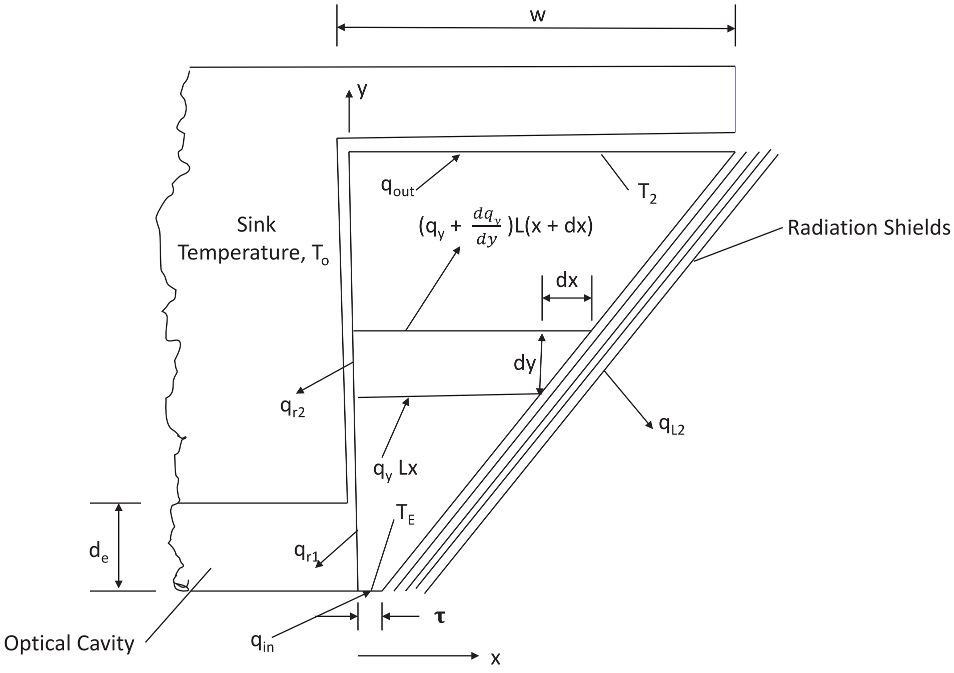

Fig. 2. Schematic for one-dimensional conduction block model.