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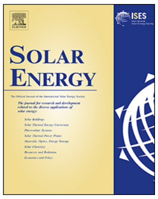

Optical analysis of a novel collector design for a solar concentrated thermoelectric generator

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ABSTRACT

This paper proposes a novel design for a solar concentrated collector for thermoelectric power generator (SCTEG), with optimum power output per unit length of collector. This collector consists of a parabolic trough concentrator (PTC) and a receiver mounted with two thermoelectric generators (TEGs) along the aperture of the concentrator. In addition to assessment of the conventional design parameters, this study investigates the effects of two new geometrical parameters on the optical performance of SCTEGs. These parameters are the vertex angle between the inner surfaces of the TEGs, and the focus offset, which is the displacement of the vertices of the TEGs above or below the focal point of the concentrator. A geometric model, which develops the basis of a ray-tracing technique for performing the optical analysis, is also described. Simulations performed for a set of design parameters showed that both parameters affected not only the optical efficiency but also the local flux distribution (LFD) on the surface of the TEGs. Iso-optical efficiency contours and numbers of LFDs were plotted, taking different values of these parameters to determine optical efficiencies. A flat-plate receiver configuration showed 85.2% optical efficiency but with a single high peak in LFD at the centre, which was undesirable. A slight alteration in vertex angle and focus offset resulted in same optical efficiency but improved LFD. The highest optical efficiency determined was 93.61% for the wide-receiver configuration. A thermodynamic analysis of the SCTEG design is also presented. This research work will assist in the development of more efficient SCTEGs.

1. Introduction

Thermoelectric generators are devices that can convert heat energy directly into electricity (Priya and Inman, 2009). Commercial versions of thermoelectric generators (also called “TEGs” or “modules”) consist of two flat substrate plates, composed of thermoelectric material in the form of thermocouples (consisting of two thermopiles), sandwiched between them, as shown in Fig. 1. One side of these modules is called the hot side and collects heat from a heat source. The other side is known as the cold side and is usually attached to a heat sink to remove waste heat.

TEGs require a temperature difference across their plates to yield an electrical output proportional to the Seebeck coefficient of the thermoelectric material inside (MacDonald, 2006). However, because of low conversion efficiencies, most of the applied studies reported in the literature have emphasised applications of TEGs for recovering waste heat (Riffat and Ma, 2003). Yodovard et al. (2001) assessed the potential of using TEGs for recovering waste heat from diesel cycle and gas turbine cogeneration in the industrial sector in Thailand; Yang (2005) gave a brief review of the integration of TEGs to recover waste heat from vehicles such as cars and trucks; Min and Rowe (2002) highlighted the use of TEGs in combined heat and power generation (cogeneration); and Doloszeski and Schmidt (1997) explored the use of TEGs with biomass.

Solar thermoelectric generators (STEGs) offer a sustainable method for producing electric output from TEGs, using heat from the sun (Xi et al., 2007). Depending on how they collect solar radiation, STEGs can be broadly classified into two major types: non-concentrating (flat-plate) and concentrating. Flat-plate STEGs consist of a chamber composed of material with a high solar transmittance, air evacuation or similar techniques for convection suppression, and solar radiation-absorbing paint on the receiving surfaces. All these features enhance thermal concentration at the hot side of TEGs. Telkes (1954) experimented with an STEG and reported an efficiency of 0.64%. Later, Goldsmid et al. (1980), Omer and Infield (1998) and Vatcharasathien et al. (2005) tried a number of more advanced materials and used different module level optimizations, but despite these efforts, very similar efficiency was achieved.

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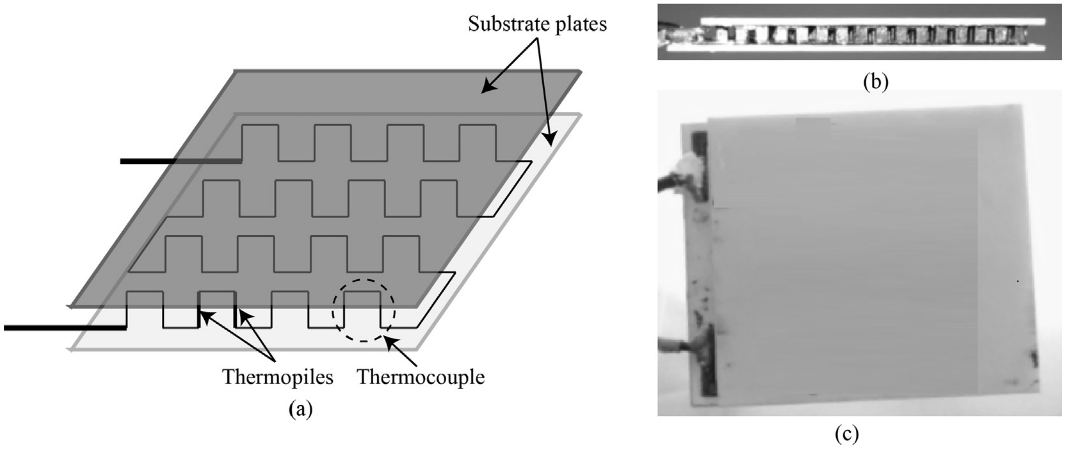

Fig. 1. Thermoelectric generator: (a) Schematic diagram; (b) Side view; (c) Top view.

However, theoretical and experimental studies on solar concentrated thermoelectric generator (SCTEGs) have shown promising results compared with former systems (Baranowski et al., 2012). A typical SCTEG collector consists of an optical concentrating device and a receiver mounted with TEGs. The concentrating devices (e.g. parabolic troughs, linear concentrators, parabolidal dishes or Fresnel lenses) focus incoming solar radiation collected over a large concentrator area onto a small receiver area. This high incident solar flux creates an effective temperature difference across the plates, which results in high power outputs (Fan et al., 2011; Nia et al., 2014).

In most of the studies of SCTEGs, the major focus has been on analyzing and optimizing the conversion of heat energy into electric energy. This has promoted research and development focused on the development of advanced thermoelectric materials (Poinas et al., 2002; Lenoir et al., 2003), module level designs (Xiao et al., 2012), thermal concentration techniques (Ogbonnaya and Weiss, 2012), and heat rejection systems (Li et al., 2010).

Although the literature reveals several studies on the assessment and improvement of the optical performance of solar collectors, most of them are relevant to conventional solar heating applications, in which the receiver is a circular pipe, prone to absorb radiation through its periphery (Nkwetta et al., 2012; Mwesigye et al., 2014). Often the outcomes from such studies are not applicable to SCTEGs because they have flat TEG receivers that can receive solar flux on the hot side only.

One optical model for SCTEGs, based on analytical geometry, was proposed by Omer and Infield (2000). The optical system was comprised of a primary parabolic trough concentrator (PTC) and a secondary compound parabolic concentrator (CPC). The TEG was attached to the base of the secondary concentrator, mounted at the focus of the PTC. The optimum sizes for both PTC and CPC were chosen so that the TEG could intercept all the reflected rays within the angular region of the incoming radiation. In a specular concentrator (with no misalignments and mirror surfaces smooth enough to reflect rays perfectly), the angular region is equal to the cone of solar radiation, with a half apex angle of $\delta_o = 16'$ (Duffie and Beckman, 2013). There are several advantages in using such a collector, but also some major limitations associated with the proposed analytical model:

It is not able to describe the local flux distribution (LFD) on the TEG surface. In general, TEGs are very sensitive to the incident heat flux. An unevenly distributed heat flux with sharp peaks may raise the temperature of some thermocouples above their material limits. This may cause damage to the module.

It is not able to predict optical efficiency, when the receiver's area is increased or decreased beyond its optimum value, keeping the concentrator diameters constant. This restricts the application of this model to use with a single TEG only. A way of adding TEGs could be to consider all of them as a single large surface, but this would eventually raise the diameter of the PTC and CPC to match the intercepts of the reflected rays. In other words, adding additional TEGs to increase power output per unit aperture area of the PTC (hereafter called "output intensity" with units of W/m^2), without changing the PTC and CPC diameter, is not possible.

It does not allow for estimating energy loss due to shadowing below the receiver. This could be critical for collectors with small concentrator diameters.

In contrast to methods based on analytical geometry, ray-tracing has proved to be an effective way to perform an exhaustive optical analysis. The technique offers flexibility in choosing any number and shape of concentrators, receivers, positions and alignments. A vast literature is also available on ray-tracing methods in conjunction with the optics of various types of solar concentrators (Groulx and Sponagle, 2010; Shuai et al., 2008; Zheng et al., 2011).

To date, little emphasis has been placed on optical modeling and optimization of SCTEGs; thus several opportunities have been missed that might have been helpful in enhancing SCTEG performance. Establishing a flexible methodology based on ray-tracing techniques could provide options for increasing output intensity by deploying more than a single module in the receiver along the concentrator's diameter, allow optimal positioning and alignment of the receiver to achieve high optical efficiency, and yield insights about LFD over the surfaces of TEGs, which would be a very significant contribution.

In this paper, a novel SCTEG collector is proposed. It can accommodate two TEGs in the receiver along the concentrator's diameter to enhance the output intensity of system. The optical performance, in terms of optical efficiency and LFD, is obtained using ray-tracing techniques. Some new geometrical design parameters not previously used in studies of SCTEGs are employed to effectively control LFD. Simulation of a set of design parameters is also performed. The optimum ranges of these parameters, within which maximum optical efficiency can be achieved, are determined using iso-optical efficiency contours. Several LFDs are also plotted using a range of values of these parameters, to select the most suitable design. The effect of optical efficiency on the overall performance of an SCTEG system is also analysed using the thermodynamic model presented in this work.

2. Methodology

2.1. Collector set-up

Of the available optical concentrators, the PTC offers ease and accuracy of solar tracking by revolving around a single axis. Small troughs can easily be built by bending a single sheet into a parabolic shape. A PTC reflects all incident solar radiation perpendicular to its aperture area, at its focus line. In an SCTEG based on a PTC, a flat receiver