Renewable Energy 120 (2018) 78–87

Contents lists available at ScienceDirect

Renewable Energy

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

A numerical study on the design trade-offs of a thin-film thermoelectric generator for large-area applications

Kirsi Tappura

VTT Technical Research Centre of Finland Ltd, P.O. Box 1300, FI-33101, Tampere, Finland

ARTICLE INFO

Article history:

Keywords:
Thermoelectric generator
Large-area TEG
Thin-film
In-plane heat transfer
FEM simulations
Computational TEG design

ABSTRACT

Thin-film thermoelectric generators with a novel folding scheme are proposed for large-area, low energy-density applications. Both the electrical current and heat transfer are in the plane of the thermoelectric thin-film, yet the heat transfer is across the plane of the module – similar to conventional bulk thermoelectric modules. With such designs, the heat leakage through the module itself can be minimized and the available temperature gradient maximized. Different from the previously reported corrugated thermoelectric generators, the proposed folding scheme enables high packing densities without compromising the thermal contact area to the heat source and sink. The significance of various thermal transport, or leakage, mechanisms in relation to power production is demonstrated for different packing densities and thicknesses of the module under heat sink-limited conditions. It is shown that the power factor is more important than *ZT* for predicting the power output of such thin-film devices. As very thin thermoelectric films are employed with modest temperature gradients, high aspect-ratio elements are needed to meet the – usually ignored – requirements of practical applications for the current. With the design trade-offs considered, the proposed devices may enable the exploitation of thermoelectric energy harvesting in new – large-area – applications at reasonable cost.

1. Introduction

There are plenty of thermal gradients available around us, which could, in principle, be exploited for sustainable energy scavenging by thermoelectric means. However, a major hurdle for a wider use of thermoelectric (TE) devices for energy harvesting is the low efficiency, which - with the conventional devices – tends to result in a high cost per converted power [1,2]. In addition, the commercially available thermoelectric devices are rigid and often relatively bulky, which limits their usage in many potential large-area applications apart from the cost. Further, most of the devices are intended for relatively large temperature gradients for which the heat leakage through the thermoelectric module itself is not as critical as for smaller gradients, while the latter are more readily available in our everyday environment.

Nevertheless, a significant number of various thermoelectric modules are commercially available, although the cost per converted power is not satisfactory for many applications. A popular approach to improve the cost competitiveness of the TE generators (TEG), is to concentrate on developing the properties of the TE materials to enhance the efficiency, or to increase the figure of merit, ZT ($ZT = S^2\sigma T/k$, where S, σ, T and k are the Seebeck coefficient, electrical conductivity, absolute temperature, and thermal conductivity, respectively) [3]. As ZT relates to the upper limit of the power conversion efficiency through the material properties, it is essential for the device optimization. However, it does not take into account the material consumption, fabrication costs, heat sink requirements or the fact that the device structure has an impact on the thermal transport mechanisms and paths [4]. Thin-film TE materials are attractive due to their potential compatibility with low-cost fabrication methods, such as roll-to-roll processing or screen printing, and lower material consumption. Flexible TEG designs, based on both organic [5,6] and inorganic [7–9] thin and thick TE films, have been studied for their potential application with arbitrary shape heat sources. The heat flux in the common thin-film TE modules is, however, perpendicular to the plane of the film, which significantly limits the temperature gradient available for power production due to the considerable thermal transport through the thin film, unless very efficient heat sinks are used [10].

Typically, TE modules consist of several n- and p-type bulk material or thin-film legs assembled as a circuit with the heat flux

E-mail address: kirsi.tappura@vtt.fi.

https://doi.org/10.1016/j.renene.2017.12.063

(temperature gradient) perpendicular to the plane of the TE module and the TE films [1,7,11,12]. For the time being, there are no commercially available TE modules where the heat flux occurs in the plane of a thin TE film, even though such an architecture allows significantly larger temperature gradients. However, there are several publications of various designs of the thin-film thermoelectric modules with the heat transfer in the plane of the TE film utilizing planar substrates [13–19], corrugated structures [20–25] or different solid supporting architectures [26,27] with some interesting approaches for flexibility and cost reduction [28–31]. They all, except some of the organic or hybrid devices [13,25,31], are designed to consist of two different TE materials to form the basic unit (TE couple) of the thermoelectric module. This traditional design employing complementary n- and p-type materials allows convenient geometries for connecting the TE legs electrically in series and thermally in parallel, but forces one to use both the n- and p-type materials in spite of their quality, which may be a challenge especially for organics devices.

Many of the reports dealing with the thin-film TE generators with in-plane heat transfer, demonstrate the device performance by applying powerful heat sinks [26,27] or forced temperature gradients [13,22,28–30] without considering the true effect of the various parasitic heat transfer mechanisms occurring in the device. However, the parasitic effects may have a significant impact on the temperature gradient, and thus, on the available power under heat sink-limited conditions. Although there are also more detailed thermal analyses performed for different planar in-plane thin-film TE structures [14–19], they do not provide insight into the designs employing a folded structure. In Ref. [21] the authors present a well-defined theoretical performance optimization for a thin-film TE generator with a corrugated architecture under heat sink-limited conditions, but neglect the influence of heat conduction through the air cavity of the device. In the present paper, it will be shown that such parasitic effects, often ignored, may have a significant impact on the temperature gradient and, thus, on the power production under natural convection, or heat sink-limited conditions, in the thin-film devices with heat transfer in the plane of the TE film fabricated on a thin substrate with low thermal conductivity. Further, as the available electrical current is usually not an issue in the bulk or thin-film TE generators where the current flows across the plane of the film, its specific influence on the device performance is normally not considered in the related reports. Unfortunately, this seems to be the case even when reporting on the thin-film TE devices with the current flow in the plane of the thin-film. The fact that the electrical resistance may become very high in the TE modules consisting of several such thin-film TE units connected electrically in series, is usually well recognized [5,23,32]. However, the significance of the available electrical current is typically not discussed in the reports, even though the produced current may be too small for practical applications, especially under modest temperature gradients [18,19,21–25,27].

In this paper, a novel folding scheme is proposed for the thin-film thermoelectric generators with the heat flux and electrical current parallel to the film surface but the temperature gradient perpendicular to the plane of the TE module. Different from the previously reported corrugated thermoelectric generators [21–25], the proposed folding enables a high packing density for the thermoelectric elements without compromising the thermal contact area to the heat source and sink. It also enables the application of only single conduction-type semiconductors as the TE materials and, thus, provides a possibility to simplify the manufacturing process and to avoid the usage of the lower quality TE materials in the module. The work concentrates on very thin TE films (400 nm) and modest thermal gradients (10–20 K) with natural convection on the cold side of the TE module without additional heat sinks, resulting to heat sink-limited conditions. Special attention is paid to the heat leakage mechanisms of the modules of different geometries and packing densities and to the impact of the electrical resistance and, in particular, the produced electrical current, on the usefulness of the TE modules for practical applications. It is shown that it is not just the maximum output power and voltage or the resistance of the module that define the performance. Instead, the available current should be of special concern when designing in-plane thin-film TE generators for specific applications. Further, the small thickness of the TE film has some implications for the conventional design parameters. For example, *ZT,* describing the material properties, is not always a good measure for predicting the power production properties of such thin-film devices.

The aim is to demonstrate the performance and design tradeoffs of the novel thin-film TE modules that can be achieved at minimal cost and are suitable for large-area, low energy-density, applications, such as energy harvesting on (or in) walls and windows or other surfaces providing appropriate temperature gradients with its environment. Deep understanding of the complex dependencies of the various design parameters can only be deduced from careful numerical studies as presented in this paper. The temperature gradients selected for this study were deduced from the long-term temperature measurements performed over and on the window glasses of VTT premised in Espoo, Finland, during a two-year period. The proposed TE module with the novel folding geometry suits well for this kind of large-area applications.

2. Materials and methods

2.1. Device architecture

The proposed TE module consists of a thin polymer, or any insulating flexible, substrate on which the planar thin-film TEGs can be fabricated with low-cost methods. A number of planar thin-film TE elements are connected electrically in series on the substrate. After the appropriate folding of the substrate, the three-dimensional (3D) TE module is formed with the TE elements connected thermally in parallel. A proposed configuration is shown in Fig. 1.

The module before folding the sheet is shown in Fig. 1a with the TE elements (or legs or TEGs) connected electrically in series (the electrical conductor lines shown in grey). The green arrows indicate the direction of the flow of the charge carriers (electrons for n-type materials, as in this study). The basic principle of operation can be understood as follows (see e.g. Refs. [25,31] for previously demonstrated single conduction type TE modules): The faster hot charge carrier (here electrons) diffuse further than the cold ones, which results to a net build-up of electrons - and, thus, a negative potential - at the cold end of each TE leg, leaving a positive potential at the hot end. In order to allow the directional charge transport and adding up the voltages, the elements are connected electrically in series by connecting the cold end (here the negative potential) of each leg to the hot end (positive potential) of the next leg with the narrow conductor lines (the grey lines in Fig. 1a). Finally, when a load is connected across the cold (−) and hot (+) ends of the TE chain as shown in Fig. 1a, the voltage produced by the TE module will cause the current to flow through the load generating electrical power. The same basic idea to connect the elements can be followed to create a module with different numbers of rows and columns. Similar TEG patterns can be printed on both sides of the substrate in order to double the TEG density. A 3D sketch and the side view of the folded module (viewed from the left side of the sheet of Fig. 1a after folding) are shown in Fig. 1b and c, respectively. Fig. 1c also depicts the possible supporting, thermally conductive structures - serving also as the thermal interfaces to the heat source