Energy Conversion and Management 81 (2014) 440–446

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Analysis of a sandwich-type generator with self-heating thermoelectric elements

Mikyung Kim [a], Hyein Yang [a], Daehyun Wee [a,b,*]

[a] Department of Environmental Science and Engineering, Ewha Womans University, Seoul 120-750, Republic of Korea
[b] Ewha Global Top 5 Research Program, Ewha Womans University, Seoul 120-750, Republic of Korea

ARTICLE INFO

Article history:
Received 13 August 2013
Accepted 16 February 2014
Available online 17 March 2014

Keywords:
Thermoelectric generators
Radioactive isotopes
Heat transfer
Efficiency
Power density

ABSTRACT

A novel and unique design of thermoelectric generators, in which a heat source is combined with thermoelectric elements, is proposed. By placing heat-generating radioactive isotopes inside the thermoelectric elements, the heat transfer limitation between the generator and the heat source can be eliminated, ensuring simplicity. The inner electrode is sandwiched between identical thermoelectric elements, which naturally allows the inner core to act as the hot side. Analysis shows that conversion efficiency and power density increase as the heat density inside the thermoelectric elements increases and as the thermoelectric performance of the material improves. The theoretical maximum efficiency is shown to be 50%. However, realistic performance under practical constraint is much worse. In realistic cases, the efficiency would be about 3% at best. The power density of the proposed design exhibits a much more reasonable value as high as 3000 W/m^2. Although the efficiency is low, the simplicity of the proposed design combined with its reasonable power density may result in some, albeit limited, potential applications. Further investigation must be performed in order to realize such potential.

1. Introduction

Thermoelectric generators, which utilize thermoelectric materials to convert heat to electricity, provide an alternative option to conventional heat engines in the field of power generation, most notably in compact waste heat recovery systems or in generic power supplies at remote, isolated locations. Typically, the maximum efficiency of thermoelectric energy conversion is presented in terms of the temperature of each heat reservoir and the thermoelectric figure of merit $ZT = S^2T/(\rho k)$, where S is the Seebeck coefficient, ρ is the electric resistivity, k is the thermal conductivity, and T is the temperature, leading to the following traditional expression for the maximum thermoelectric conversion efficiency (η_0) [1]:

$$\eta_0 = \frac{T_h - T_c}{T_h} \frac{\sqrt{ZT+1} - 1}{\sqrt{ZT+1} + T_c/T_h}, \qquad (1)$$

where ZT is typically evaluated at the mean temperature (T_m) of the hot-side temperature T_h and the cold-side temperature T_c. From the equation, it is clear that the increase of ZT leads to the increase of the energy conversion efficiency, and significant efforts have been exerted on creating materials with high ZT values. Nanowires [2], thin films [3], and materials with grain boundaries [4] have also been investigated, showing various degrees of success in improving ZT.

However, conventional thermoelectric generators do not perform as well as promised. Many factors are contributing to the performance gap between the theoretical estimate of thermoelectric materials and the actual performance of conventional thermoelectric generators. One of the most significant contributors is the limited heat transfer between the hot- and/or cold-side thermal reservoirs and the generator itself [5]. Large temperature difference typically occurs between the heat source (or sink) and the generator due to a poor heat transfer coefficient. The actual temperature difference across thermoelectric elements made of thermoelectric materials becomes small as a result. With a small actual temperature difference, the performance of thermoelectric materials, which is relatively poor already, suffers even more in real-world applications.

In this article, we study the feasibility of a self-heating thermoelectric generator, in which thermoelectric materials create their own heat. Since the thermoelectric elements heat themselves, there is no need for engineering a good thermal interface between the hot-side thermal reservoir and the generator, which eliminates the difficulty of achieving good heat transfer, at least on one side.

* Corresponding author at: Department of Environmental Science and Engineering, Ewha Womans University, Seoul 120-750, Republic of Korea.
E-mail address: dhwee@ewha.ac.kr (D. Wee).

http://dx.doi.org/10.1016/j.enconman.2014.02.061
0196-8904/

Self-heating thermoelectric materials are not being utilized yet, but there does exist certain prospect for such development. One potential way to develop such materials is to incorporate radioactive isotopes in traditional thermoelectric materials. For example, a known thermoelectric oxide ($SrTiO_3$) [6,7] can be altered into a self-heating thermoelectric oxide by replacing regular atoms (Sr) with radioactive isotopes (^{90}Sr). Another method is to fill radioactive isotopes into a skutterudite, which is one of the most promising thermoelectric materials [8]. Radioactive isotopes were previously used as a heat source in the context of thermoelectric generation in space missions [9,10] and in isolated monitoring sites [11]. In particular, the use of ^{90}Sr in the form of $SrTiO_3$ as a heat source was already reported [12], but combining radioactive isotopes with thermoelectric elements is a possibility that has been hardly explored before.

The paper is organized as follows. In Section 2, first, we describe the proposed design of a thermoelectric generator using self-heating thermoelectric materials. Then, we continue to discuss our method of analysis for evaluating the performance of the generator. In Section 3, the method described in Section 2 is applied while changing the design parameters within realistic ranges in order to evaluate the performance indices of the proposed design. In Section 4, conclusions are drawn by summarizing and discussing the results.

2. Analysis of the proposed design

Our proposed design is presented in Fig. 1. Unlike conventional thermoelectric modules, there is no external heat source other than the self-heating thermoelectric elements inside the generator. Hence, there is no distinction between the hot side and the cold side specified by external thermal reservoirs. Only with appropriate thermal boundary conditions imposed, can a proper temperature difference across a thermoelectric element be developed. The use of a sandwich-like shape, where the inner electrode is located between two identical thermoelectric elements, is used to achieve such boundary conditions in a straightforward fashion. The inner boundary becomes naturally adiabatic, which renders the inner core as the hot side.

For simplicity, we only consider one single unipolar element in our analysis. Since the entire generator is constructed by alternating concatenation of two different types of unipolar elements, the performance of the entire generator can be analyzed by summing the power output of all elements. The governing equation describing the temperature distribution (T) in one single unipolar element is given as follows:

$$\frac{d}{dx}\left(k\frac{dT}{dx}\right) + \rho j^2 + \dot{q} = 0. \tag{2}$$

x is the variable for the outward longitudinal coordinate. k and ρ are the thermal conductivity and the electrical resistivity of the thermoelectric element, respectively. j is the current density, and $\dot{q}$ is the amount of heat generated per unit volume, which is uniform and constant between $x = 0$ and L. Because the purpose of the analysis is a preliminary evaluation of feasibility, only minimal functional features are included in Eq. (2). For instance, the Thomson effect is excluded, although it may affect actual performance [13]. Another effect neglected here is that of interfacial Ohmic heating, which is an important mechanism causing losses in traditional thermoelectric modules, where the leg length of each thermoelectric element is relatively small, like several millimeters. In the present design, however, the leg length must be much larger, since each leg must act as its own heat source as well. As shown in Section 3, the leg length of each thermoelectric element may reach more than 5 cm. Using the value of resistivity in Table 1, the value of the electrical resistance of one leg per unit area is estimated to be $15 \times 10^{-3}\ \Omega\,cm^2$. It was reported that the interfacial resistance of a typical thermoelectric module is on the order of $10^{-6}\ \Omega\,cm^2$ [14]. Thus, it is clear that the interfacial Ohmic heating may be neglected without too much loss of generality.

The corresponding boundary conditions are given by:

$$jST - k\frac{dT}{dx} = 0 \quad \text{at} \quad x = 0, \tag{3}$$

and

$$T = T_c \quad \text{at} \quad x = L. \tag{4}$$

Here, S is the Seebeck coefficient of the thermoelectric element, L is the coordinate of the outer boundary, and T_c is the temperature of the cold-side end. The first term on the LHS of Eq. (3) represents the Peltier heat. From Eqs. (2)–(4), dimensionless equations are constructed by defining $\theta = T/T^*$ and $\xi = x/L$. T^* is a characteristic temperature, which is given here as $T^* = \dot{q}L^2/k$. The set of corresponding dimensionless equations are:

$$\frac{d^2\theta}{d\xi^2} + \nu + 1 = 0, \tag{5}$$

$$\mu\theta - \frac{d\theta}{d\xi} = 0 \quad \text{at} \quad \xi = 0, \tag{6}$$

and

$$\theta = \theta_c \quad \text{at} \quad \xi = 1, \tag{7}$$

where $\theta_c = T_c/T^*$, $\mu = jSL/k$, and $\nu = \rho j^2/\dot{q}$. The solution to Eqs. (5)–(7) is given as follows:

$$\theta(\xi) = \frac{(1+\mu\xi)(1+\nu+2\theta_c) - (1+\mu)(1+\nu)\xi^2}{2(1+\mu)}. \tag{8}$$

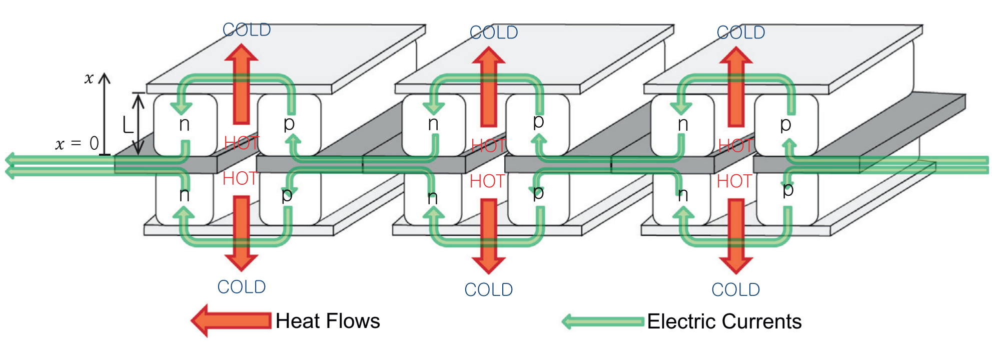

Fig. 1. Schematic illustration of the proposed design of a sandwich-type generator with self-heating thermoelectric elements.