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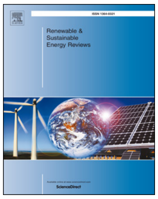

A review of the development and applications of thermoelectric microgenerators for energy harvesting

O.H. Ando Junior[*], A.L.O. Maran, N.C. Henao

Departament of Renewable Energies, UNILA, Federal University of Latin American Integration, Av. Sílvio Américo Sasdelli, 1842 Foz do Iguaçu, PR, Brazil

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ABSTRACT

Studies concerning the use of thermoelectric effect for the conversion of thermal energy into electricity have become increasingly numerous since applications of the thermoelectric phenomenon can be limitless. Thermoelectric Generators (TEG) have shown promising results in combustion vehicles, with an overall efficiency increment from 33% to 57%, in addition to an increase of 6% in the available power in an automobile. In the aerospace industry, thermoelectric devices have been employed due to the need of making the most of the available energy. Thermoelectric modules are also used in the harvest of waste heat in wood stoves, furnace walls, and industrial chimneys. In Bioengineering, there are applications for small-scale generation including the use of heat from the human body to feed microelectronic devices and autonomous sensors. Therefore, the article shows a review of the use of thermoelectricity for the energy harvesting, beginning with the main concepts and definitions on the subject, followed by the state of the art containing the main methods and advances in science and technology for the development and application of solid-state micro-generators to capture residual energies.

1. Introduction

Energy and the demand for alternative resources are crucial for all countries. Electricity is critical for both social and economic growth, however, there is an energy crisis that evidenced the limits of the energy supply to meet the growing demand [1,2]. Therefore, it is important to explore alternative resources that lead to environmentally sustainable solutions to diversify the energy matrix and reduce environmental impacts [3]. In Brazil, one of the greatest challenges is increasing the use of natural resources, spread in a heterogeneous way, in the most varied regions of the country, however, their potential for power generation from renewable resources is among the largest in the world [4]. The relevance of harvesting residual energy is the fact that it is an alternative source and depends only on thermal losses. Usually, such energy losses are originated from industrial processes and released to the environment without any recovery. Waste will not cease to exist and to be released into the environment, but it can be partially used to generate electricity at the very site, increasing the overall performance of the system.

When a temperature gradient is available in some certain environments there is a potential power generation using thermal energy where the temperature difference represents the potential for energy conversion and the heat flow provides the power. As thermoelectric devices have their efficiencies under Carnot limit, the generated power rates are usually low but thermoelectricity might be attractive for applications with low power requirements.

Several types of research have been directed towards finding new high-performance materials (especially using nanostructures) or improving the performance of conventional thermoelectric converters, with the main objective of refrigeration in household appliances [11] and the generation of electricity through the capture of residual energy. Some recent studies show advances in the development of thermoelectric materials with rare earths reaching efficiencies higher than 20% [5]. Products for the Peltier effect are commercially available, such as drinking fountains, cellars, incubators, organ transport boxes, vaccine storage chambers, portable pharmaceutical refrigerators, among others. Such devices use electricity for refrigeration and heating of containers [12]. In automobiles, reusing part of the thermal energy released in the exhaust system began to show progress very recently. The first thermoelectric generator was constructed and published by Neild in 1963 [9]. The use of thermoelectric modules is limited to small volumes and localized cooling to meet its technical and economic feasibility [5].

Abbreviations: Bi_2Te_3, Bismuth Telluride; *BSST*, Thermoelectric material manufacturer; *DC*, Direct Current; *IAV*, Ingenieurgesellschaft Auto und Verkehr; *JPL*, Jet Propulsion Laboratory; *MMRTG*, Multi-Mission Radioisotope Thermoelectric Generator; *NASA*, National Aeronautics and Space Administration; *NTC*, Negative Temperature Coefficient; *PbTe*, Lead Telluride; *RTG*, Radioisotope Thermoelectric Generator; *SiGe*, Silicon-germanium; *TGE*, Thermoelectric Generator

[*] Corresponding author.

E-mail addresses: oswaldo.junior@unila.edu.br (O.H. Ando Junior), anderson.maran@unila.edu.br (A.L.O. Maran), nelson.henao@aluno.unila.edu.br (N.C. Henao).

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List of symbols

A	Contact area, [m^2]
I	Current, [A]
k	Thermal conductivity, [W/(m·K)]
P	Power, [W]
Q	Thermal energy, [J]
Q_c	Heat absorbed at the junction, [W]
R	Electrical resistance, [Ω]
T	Temperature, [°C]
T_c	Cold side temperature, [°C]
T_h	Hot side temperature, [°C]
V	Voltage, [V]
ZT	Figure of merit, [1/K]
α	Seebeck coefficient, [mV/°C]
ΔT	Temperature variation, [°C]
ΔV	Voltage variation, [V]
η	Efficiency, [-]
π	Peltier Coefficient, [V]

Much has been discussed about clean and renewable power sources, consequently, the energy coming from the thermoelectric phenomenon has emerged as an alternative among the various possibilities. The use of thermoelectric modules has certain advantages, such as high durability, high precision, and reduced volume, as well as being an excellent way of collecting residual thermal energy, and also the possibility of use in a clean cogeneration process [13–17].

In this article, we first approach the main concepts of thermoelectricity discussing the relation between thermal and electrical variables, first observations of the thermoelectric effect are also mentioned, most commonly used materials and thermoelectric modules assembly. The state of the art section brings a summary of the main applications, which includes collecting residual heat in combustion-driven vehicles, air-crafts, home, industrial, solar and microelectronic devices. We also make a number of considerations that can be adopted when designing and developing thermoelectric-based energy harvesters.

2. Thermoelectricity

2.1. Historical evolution of thermoelectricity

Thermoelectricity is the conversion of thermal energy into electricity through a temperature gradient. Thomas Johann Seebeck, born in Reval (now Tallinn), Estonia, in 1770, was the physicist precursor of the thermoelectric effect which is reversible and can be subdivided into the Seebeck, Peltier, and Thomson effects [2,7,8]. The Seebeck effect was accidentally discovered in 1821, by Thomas Seebeck, who observed that two semiconductors from different materials connected at their ends, under a temperature difference, caused a needle, positioned between them, to be displaced [7]. Between 1822 and 1823 Thomas Seebeck published his results affirming that different conductors (or semiconductors) produce a voltage when connected at their extremities and subjected to a temperature gradient [9].

In the 1960s, the thermoelectric phenomenon was at its peak when it was believed that all refrigeration applications would soon be replaced by devices based on Peltier Effect. [10] In the last four decades, there has been no major development in the area. The coefficient of performance of the devices for cooling by Peltier effect is still 4–5 times below the coefficient of the conventional refrigeration systems [9,10]. As new materials and processing methods emerge, thermoelectricity has been attracting the interest of scientific research and the industry. The applications of cooling (laser modules, biomedical applications) and power generation for use in autonomous chips, where the use of batteries is not adequate, has motivated the interest in this area [9].

2.2. The seebeck effect

This phenomenon occurs when a temperature difference is applied between the ends of a material causing the movement of electrons to the region with lower energy level and increasing the concentration of positive ions in the other region. The movement of the electrons generates an electric voltage, which is proportional to the temperature difference [2], as shown in Fig. 1.

The Seebeck coefficient (α) is equal to the voltage generated (1) between two points of a conductor when the bimetallic junction is subjected to a temperature gradient (ΔT) of 1 K [8–10]. The generation of electrical voltage from a conductor exposed to a temperature gradient is called the Seebeck effect. The efficiency is given by α and is determined by the scattering rate and the density of the conduction electrons, being defined as the relation between the electric voltage generated and the temperature difference [11].

$$\Delta V = \alpha(T_1 - T_2)[\mathrm{V}] \tag{1}$$

$$\alpha = \Delta V/\Delta T\,[\mathrm{V/K}] \tag{2}$$

A good thermoelectric material has a Seebeck coefficient (α) between 100 mV/K and 300 mV/K [11]. Thus, to achieve some voltage many thermoelectric pairs connected in series are required as can be seen in Fig. 1(b) [11].

The Peltier effect was discovered a few years later in 1834, when a French physicist named Jean Charles Athanase Peltier discovered the opposite effect to the Seebeck, that is, when an electric current (DC) flows in the circuit composed of a bimetallic junction it causes the

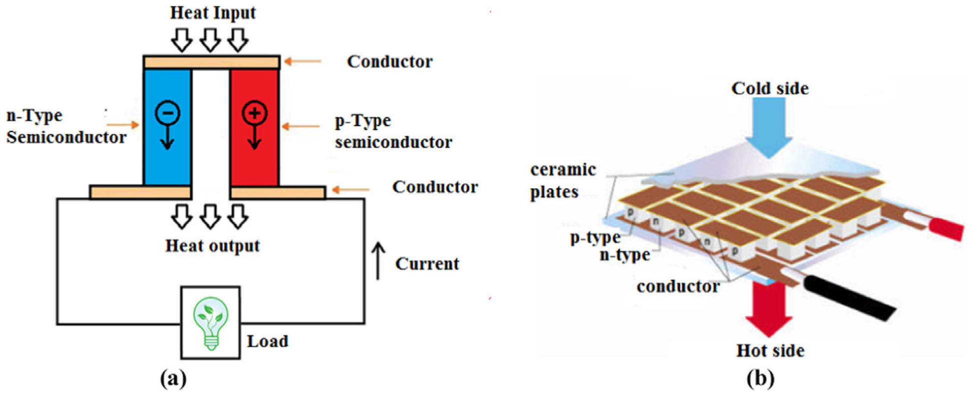

Fig. 1. Demonstration of *Seebeck* Effect [9].