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Thermoelectric generators: Linking material properties and systems engineering for waste heat recovery applications

Saniya LeBlanc *

Department of Mechanical & Aerospace Engineering, The George Washington University, Washington, DC 20052, USA

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ABSTRACT

Waste-heat recovery with thermoelectric power generators can improve energy efficiency and provide distributed electricity generation. New thermoelectric materials and material performance improvements motivate development of thermoelectric generators for numerous applications with excess exhaust and process heat. However, thermoelectric generator product development requires solving coupled challenges in materials development and systems engineering. This review discusses these challenges and indicates ways system-level performance relies on more factors than traditional thermoelectric material performance metrics alone. Relevant thermo-mechanical and chemical material properties, system components such as thermal interface materials and heat exchangers, and system form factors are examined. Manufacturing processes and total system cost components are evaluated to provide product development and commercial feasibility contexts.

1. Introduction

Thermoelectric devices offer a unique power generation solution because they convert thermal energy into electricity without requiring moving components. Thermoelectric generators have been proposed for waste-heat recovery applications, and advancements in thermoelectric materials development have highlighted the technology's energy efficiency and commercial potential. To realize this potential and improve thermoelectric power generation feasibility, the gap between thermoelectric materials development and generator systems engineering must be closed. The thermoelectric generator materials characteristics are particularly important because it is a solid-state energy conversion device. Electron and thermal transport through multiple materials in the device is paramount and affects overall system performance. This review provides a systems-level perspective of thermoelectric generator development. It underscores the relationships between thermoelectric materials development goals and generator system requirements. Considerations for system components beyond the thermoelectric materials are discussed along with manufacturing and cost issues.

A thermoelectric (TE) module consists of units, or legs, of n- and p-type semiconducting materials connected electrically in series and thermally in parallel. The figure of merit ZT describes material performance. It depends on the thermoelectric material properties Seebeck coefficient S, electrical conductivity σ, and thermal conductivity k, and $ZT = S^2\sigma T / k$ where T is the temperature of the material. A TE couple is one pair of n- and p-type legs, and a module generally has several couples. These couples and their electrical interconnects are enclosed by an electrical insulator, typically a ceramic. A typical off-the-shelf module is shown in Fig. 1. As depicted in Fig. 2, a thermoelectric generator (TEG) is usually a more extensive system than the module. In a TEG, the modules are connected thermally in parallel with heat exchangers to facilitate the transfer of heat from the heat source to the module's hot side and away from its cold side. The modules are connected to an electrical load to close the circuit and enable electricity extraction.

Thermoelectric generators have been used to power space vehicles for several decades [1,2], so the research and development contributions and expertise from the space industry are invaluable in the development of terrestrial waste-heat recovery TEGs. Named radioisotope thermoelectric generators (RTGs), the heat source in spacecraft TEGs comes from the nuclear decay of radioactive isotopes. RTGs were selected to power space vehicles since they are highly reliable, robust, and compact. They are solid-state devices without the rotating machinery typical of other heat engines, so RTGs do not produce noise or vibration. These qualities made RTGs ideal for powering autonomous space vehicles with long life missions. RTGs for space power systems have unique characteristics which differentiate this application from the waste-heat recovery applications discussed here. The heat source temperature is typically higher (~1000 °C) resulting in the use of thermoelectric materials such as silicon germanium which are suitable for high temperature power generation. The operating environments are outer space and other planetary surfaces. Moreover, the cost–performance considerations and constraints for space vehicle development are significantly different than for waste-heat recovery applications since significant

* 801 22nd Street NW, Phillips Hall, Suite 739, Washington, DC 20052, USA. Tel.: +1 202 994 8436; fax: +1 202 994 0238.
E-mail address: sleblanc@gwu.edu.

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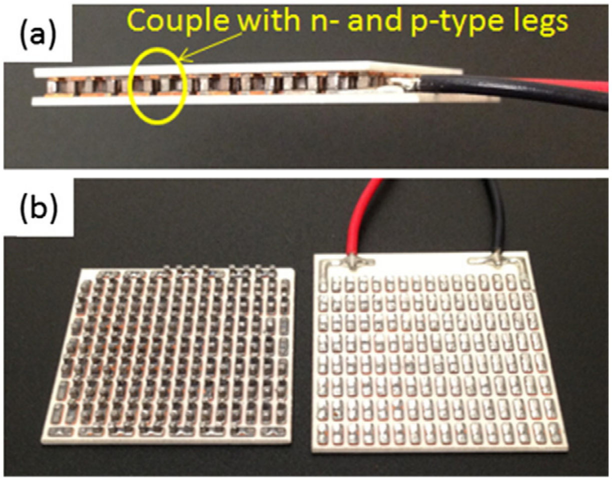

Fig. 1. Pictures of an off-the-shelf thermoelectric module. (a) Side view showing multiple thermoelectric leg couples. (b) Interior of module with one substrate removed to reveal the electrical interconnects and solder joints. The module pictured is approximately 1 in. by 1 in. and supplied by Marlow Industries, Inc.

value is placed on the RTG primary power generation capability and unique suitability for the requirements of space applications.

From electronics to industrial furnaces, numerous waste-heat sources at low- (<250 °C), mid- (~250-650 °C), and high- (>650 °C) temperatures exist. TEGs have mostly been proposed for waste-heat recovery in mid- and high-temperature applications such as automotive, engine, and industrial applications with untapped exhaust and process heat because of the potential for appreciable power generation [3–5]. The mid- to high-temperature exhaust and process heat types of applications are the focus of the discussion here, and sample heat source temperatures and applications are shown in Table 1. Vehicle applications include passenger vehicles and large trucks, and prototypes have already been demonstrated [5,6]. There are a myriad of industrial processes such as steel making and glass melting, and a comprehensive assessment of industrial waste-heat opportunities in the United States was conducted in 2008 [3]. The study notably indicated that thermoelectric generation had not been demonstrated in U.S. industrial applications. In Asia, particularly Japan, there have been multiple demonstrations of TEG waste-heat recovery [7,8] with a recently deployed TEG generating 250 W from a steel casting line [9].

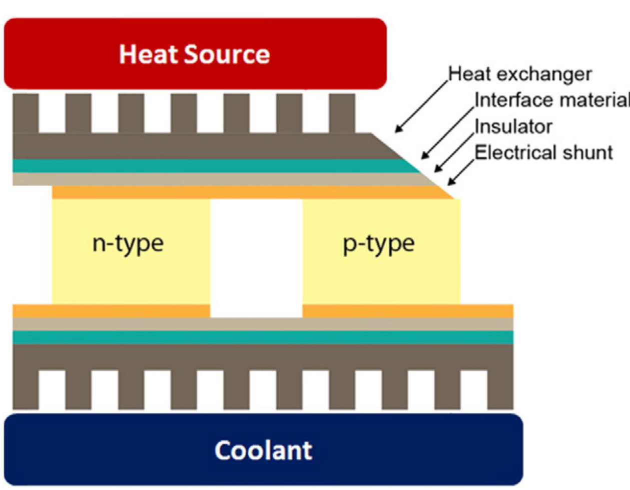

Fig. 2. Schematic of one thermoelectric couple in a thermoelectric generator system. A module consists of many couples between electrical insulators. The modules are connected to heat exchangers to interface with thermal reservoirs in the waste-heat recovery application.

Table 1
Approximate waste-heat source temperatures are provided for sample mid- and high-temperature TEG applications. Temperatures will vary based on TEG position in the system, and the temperature at the hot side of the thermoelectric will be lower than the heat source temperature.

Application	Heat source temperature	Reference
Automotive exhaust	400–700 °C	[10]
Diesel generator exhaust	~500 °C	[11]
Primary aluminum Hall–Heroult cells	700–900 °C	[3,4]
Glass melting regenerative furnace	~450 °C	[3,4]

As in space applications, key advantages of TEGs for waste-heat recovery are their simplicity, minimal maintenance requirements, and reliability since there is no rotating machinery in the system. Disadvantages include low efficiencies, high costs, and systems integration barriers. The assessment for TEG waste-heat recovery potential often focuses on the heat source temperature where high-temperature processes are favorable. Government-initiated studies and funding for TEGs reflect the interest in these promising, high-temperature industrial process applications. Additionally, a crucial consideration for TEG product development and commercial viability is identifying the appropriate fit between the product and potential markets [12]. The commercial drivers for product–market fit can lead to preference for mid-temperature applications over high-temperature applications. This product–market fit is closely related to practical materials development and systems engineering needs which do not necessarily correlate to obtaining higher material *ZT* values.

The following discussion provides key points about the link between TEG material properties and system performance. The target readers for this overview are those who are outside the hermoelectrics research and development community and/or want to understand overarching key issues with thermoelectric materials and systems development. Readers who are interested in the extensive literature on thermoelectric materials [13–16], systems design and development [11,17–20], and specific applications [21–23] are referred to more specialized books [16,24,25] and literature. In this review, an overview of thermoelectric materials considerations is followed by a description of system components and design factors and a comparison of material versus system performance metrics. Lastly, an overview of systems manufacturing and cost considerations is provided with particular attention paid to materials concerns.

2. Materials overview

Thermoelectric materials are typically classified by material structure and composition. Some of the main classifications are chalcogenide, clathrate, skutterudite, half-Heusler, silicide, and oxide. Excellent reviews of thermoelectric materials have provided descriptions of both the material classifications and the relationship between material structure and thermoelectric properties [13,14,26], so comprehensive descriptions are not provided here. Chalcogenide materials have a long history of demonstrated thermoelectric use with bismuth telluride and lead telluride being the most prominent. Commercial, off-the-shelf thermoelectric modules for low temperature use are primarily made with bismuth telluride and its solid solutions with antimony or selenium. Lead telluride has better thermoelectric properties at higher temperatures (~500–600 °C). Materials engineering of clathrates and skutterudites has involved introduction of void-filling or guest atoms into a base structure. These additions can optimize electron concentration or act as phonon scattering sites. Such materials engineering to achieve a glass-like thermal conductivity combined with good charge carrier mobility has been termed the “phonon glass electron crystal” approach. With one vacant sublattice in the crystal structure, the properties of half-Heusler materials have also been improved through void-filling as well as doping of the filled sublattices. Silicides have generated interest due to the low cost of their abundant materials (*i.e.*