Energy Conversion and Management 105 (2015) 946–950

Contents lists available at ScienceDirect

Energy Conversion and Management

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

High-temperature and high-power-density nanostructured thermoelectric generator for automotive waste heat recovery

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ARTICLE INFO

Article history:
Received 29 May 2015
Accepted 20 August 2015

Keywords:
Nanostructured material
Thermoelectric generator
Waste heat recovery
Energy efficiency

ABSTRACT

Given increasing energy use as well as decreasing fossil fuel sources worldwide, it is no surprise that interest in promoting energy efficiency through waste heat recovery is also increasing. Thermoelectric generators (TEGs) are one of the most promising pathways for waste heat recovery. Despite recent thermoelectric efficiency improvement in nanostructured materials, a variety of challenges have nevertheless resulted in few demonstrations of these materials for large-scale waste heat recovery. Here we demonstrate a high-performance TEG by combining high-efficiency nanostructured bulk materials with a novel direct metal brazing process to increase the device operating temperature. A unicouple device generates a high power density of 5.26 W cm^{-2} with a 500 °C temperature difference between hot and cold sides. A 1 kW TEG system is experimentally demonstrated by recovering the exhaust waste heat from an automotive diesel engine. The TEG system operated with a 2.1% heat-to-electricity efficiency under the average temperature difference of 339 °C between the TEG hot- and cold-side surfaces at a 550 °C exhaust temperature. The high-performance TEG reported here open up opportunities to use TEGs for energy harvesting and power generation applications.

1. Introduction

As global energy consumption continues to increase, it is imperative to develop new technologies to increase energy efficiency and reduce fossil fuel consumption. Thermoelectric generators (TEGs) are one of the most attractive waste heat recovery approaches given their solid-state and compact nature.

Thermoelectric material performance is determined by the thermoelectric figure of merit, defined as $ZT = (\alpha^2\sigma/\kappa)T$, where α, σ, κ are the Seebeck coefficient, electrical conductivity, thermal conductivity of materials, respectively, and T is the absolute temperature [1,2]. The TEG can operate under either maximum power or maximum efficiency conditions. For waste heat recovery applications, the TEG maximum performance and cost ratio can be obtained at the maximum power condition, where the heat-to-electricity conversion efficiency η_{te} can be approximated as:

$$\eta_{te} = \frac{T_h - T_c}{T_h}\frac{ZT_h}{ZT_m + ZT_h + 4} \quad (1)$$

where T_c and T_h are the temperatures on thermoelectric device cold side and hot side respectively, and ZT_h and ZT_m is the ZT at T_h and the mean ZT of the thermoelectric material between T_c and T_h [1,3].

In addition to η_{te}, the TEG electrical power density is another important metric that directly impacts the TEG performance and cost ratio, which is especially important for waste heat recovery applications [3]. The TEG power density can be increased by improving the materials ZT, increasing the temperature difference ΔT across the TEG, and by optimizing thermoelectric element dimensions and filling factors.

In recent years, TEGs have attracted a great deal of interest due to the increased material ZT realized mainly through nanostructuring [4–16]. Despite significant ZT increases, there have been numerous challenges in using these nanostructured materials for waste heat recovery applications due to their relatively poor thermal stability and low mechanical strength at high temperatures as well as difficulties in making reliable electrical contacts with low contact resistances [17].

The majority of the previous research on TEG for waste heat recovery has focused on the theoretical study of TEG design and optimization [18–24]. There have been a few reports of experimental demonstration of low-temperature waste heat recovery using

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http://dx.doi.org/10.1016/j.enconman.2015.08.051
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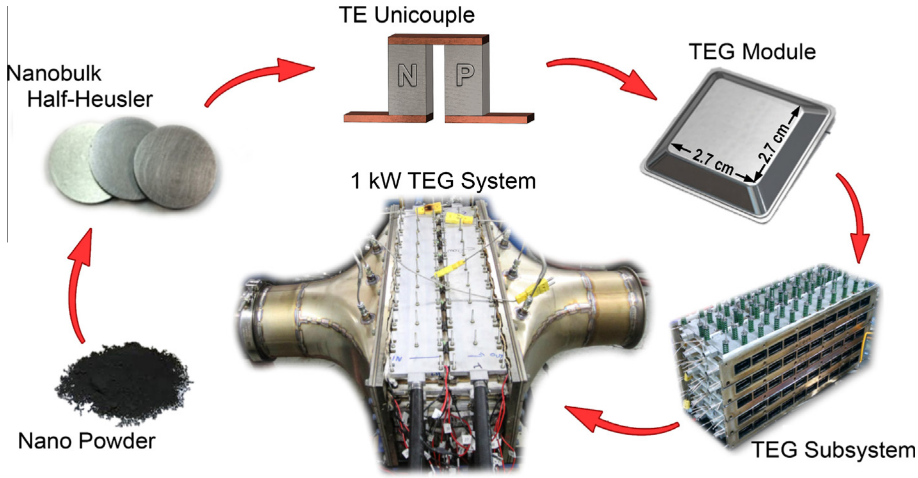

Fig. 1. Pictures illustrating the fabrication processes of the high-performance TEG. The nanobulk half-Heusler is fabricated by hot pressing the nano-powders processed with ball milling. The thermoelectric unicouple is fabricated by brazing the *n*- and *p*-type thermoelectric elements onto copper electrodes. The TEG module includes 28 unicouples in a sealed enclosure with two electrodes, and the TEG system includes an assembly of 400 TEG modules with heat exchangers and cold plates.

TEGs [25–28]. However, these TEGs were fabricated using conventional thermoelectric materials with low ZT that can only operate at hot-side temperatures below 200 °C, resulting in very low efficiency and power density. In order to make TEG a commercially-viable technology for automotive waste heat recovery, TEGs need to be able to operate at exhaust temperatures above 500 °C, and with high power density and low cost.

Here we report a high-temperature TEG with high power density of 5.26 W cm^{-2} operating under 500 °C temperature difference between the hot side and the cold side (shown in Fig. 1). The TEG is fabricated using high ZT nanostructured bulk (nanobulk) half-Heusler alloys using a highly scalable process [29–32]. A 1 kW TEG system is experimentally demonstrated by converting the waste heat on an automotive diesel engine into electricity.

Table 1
Size and mean thermoelectric properties between 100 and 600 °C for the half-Heusler elements used in the TEG module.

Half-Heusler elements	*N*-type	*P*-type
Size (mm^3)	1.8 × 1.8 × 2	1.8 × 1.8 × 2
Seebeck coefficient (μV/K)	−191	191
Thermal conductivity (W/m K)	3.4	3.0
Electrical conductivity (10^5 S/m)	1.15	0.69
ZT	0.78	0.52

2. Thermoelectric generator (TEG) module fabrication

The TEG module (shown in Fig. 1) is the core component dominating TEG system performance. In this work, the high-temperature TEG was fabricated using nanobulk half-Heuslers synthesized via a ball milling and hot press process [29–32]. The *n*-type and *p*-type nanobulk half-Heuslers have peak ZT of 1.0 at 500 °C and 0.9 at 700 °C, which are 25% and 80% higher than their non-nanostructured bulk counterparts, respectively [29–32]. Table 1 shows the dimensions and mean thermoelectric properties of the half-Heusler elements calculated from 100 to 600 °C.

In addition to the enhanced ZT, the nanobulk half-Heusler materials show comparable thermal stability and improved mechanical strength as compared to their bulk counterparts [33], which are critical to fabricate robust high-temperature TEGs. We developed a unique process to directly braze the *n*-type and *p*-type half-Heusler elements to copper electrodes at 825 °C in vacuum using the silver and copper based brazing alloy (Incusil-ABA) in order to construct unicouple devices. This simplified metal contact technique provides not only very low contact resistivity of ~1 μΩ-cm^2, but also very high tensile bonding strength of 40 MPa, which compares favorably with state-of-the-art complicated metallization processes [34].

As shown in Fig. 2a, the unicouple device produces an ultrahigh power density of 5.26 W/cm^2 with respect to the thermoelectric

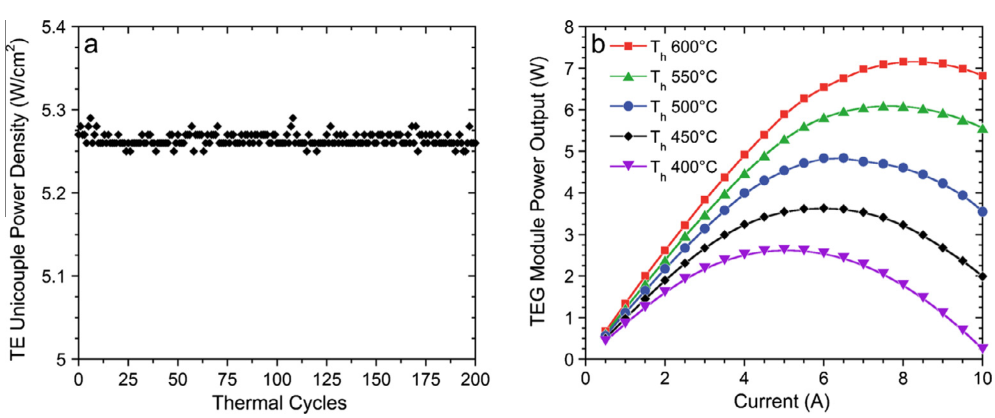

Fig. 2. (a) The thermoelectric unicouple power density tested at 600 °C on the hot side and 100 °C on the cold side for 200 thermal cycles; and (b) the packaged TEG module power vs. electric current for various hot-side temperatures and a constant cold-side temperature of 100 °C.