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Research Paper

High-performance nanostructured thermoelectric generators for micro combined heat and power systems

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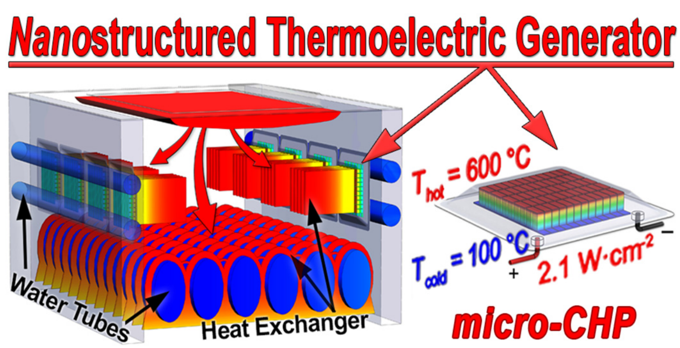
HIGHLIGHTS

- A TEG is fabricated using high-efficiency nanostructured thermoelectric materials.
- The TEG produces high power density of 2.1 W/cm^2 with 5.3% electrical efficiency.
- A micro-CHP system is demonstrated by integrating the TEG into a gas-fired boiler.

GRAPHICAL ABSTRACT



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ABSTRACT

Micro combined heat and power (micro-CHP) systems are promising pathways to increase power generation efficiencies. Here a new class of micro-CHP system without moving parts is experimentally demonstrated by integrating high-temperature thermoelectric generators (TEGs) and residential gas-fired boilers, thus enabling wide applications. The TEGs fabricated using high-efficiency nanostructured bulk half-Heusler alloys generate ultrahigh power density of 2.1 W/cm^2 with 5.3% electrical efficiency under 500 °C temperature differences between the hot and cold sides. The TEG system harnesses the untapped exergy between the combustion gas and water, and converts thermal energy into electric power with 4% heat-to-electricity efficiency based on the total heat input into the TEGs. The high-performance TEGs open lots of opportunities to transform power generation technologies and improve energy efficiency.

1. Introduction

In recent years, micro combined heat and power (micro-CHP) systems have been of increasing interests as they offer high-efficiency and off-grid energy solutions for residential applications [1]. There are several reasons for the growing interests in micro-CHP systems. First, micro-CHP systems increase the overall fuel efficiency due to the local production and usage of heat and power at a common location, which not only avert energy losses due to transportation but also lead to effective usage of waste heat accompanied with power generation processes. Second, micro-CHP systems can supplement the intermittence of most renewable energy systems [2] and increase energy security for areas vulnerable to power outage. Third, micro-CHP systems are attractive due to their environmental merits via the reduction of CO_2 emissions [3]. Currently, there are a few micro-CHP technologies, including fuel cells, Stirling engines, and internal combustion engines, etc. Despite the high electrical efficiency of 20–40%, the above technologies are facing

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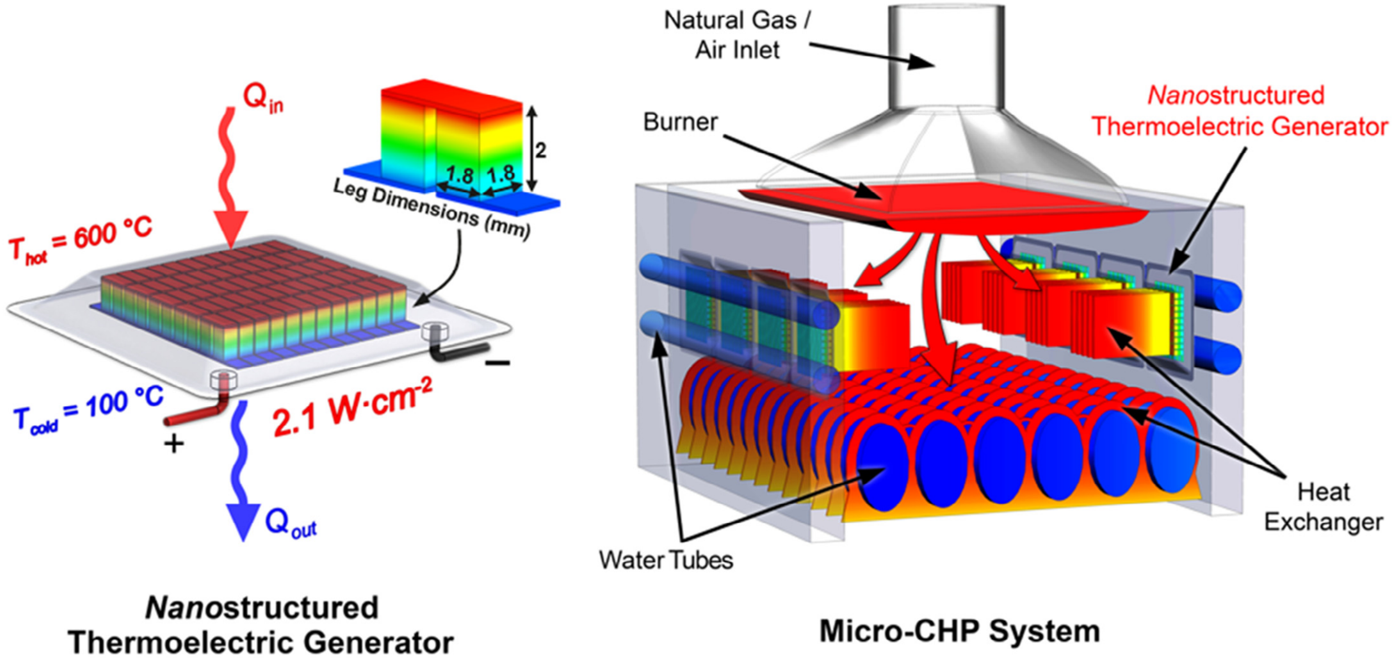

Fig. 1. Schematic design of a micro-CHP system, using nanostructured bulk TEGs sandwiched between a combustion gas heat exchanger and the boiler water tubes, for maximum temperature gradient. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

challenges such as high cost or maintenance issues associated with moving parts, which limit their applications [4,5].

Thermoelectric generators (TEGs) present a new opportunity for high-performance and low-cost micro-CHP systems. Based on the Seebeck effect, TEGs enable the direct conversion of heat into electricity without moving parts [6]. The TEG based micro-CHP system is advantageous due to its completely solid-state nature, which enables reliable, cost-effective, and quiet operation that is unattainable from most CHP technologies. The TEG heat-to-electricity conversion efficiency η_{te} can be approximated as [6],

$$\eta_{te} = \frac{T_h - T_c}{T_h} \frac{\sqrt{1+(ZT)_M} - 1}{\sqrt{1+(ZT)_M} + \frac{T_c}{T_h}} \quad (1)$$

where T_h and T_c are the temperatures on the hot side and cold side of thermoelectric devices, respectively, and $(ZT)_M$ is the mean thermoelectric material figure of merit between T_h and T_c. The ZT is a dimensionless number defined as $ZT = (\alpha^2\sigma/k)T$, where α, σ and k are the Seebeck coefficient, electrical conductivity, thermal conductivity, respectively, and T is the absolute temperature [6,7].

Besides η_{te}, the TEG electrical power density is another important criterion that directly determines the power unit cost for TEG systems [8]. Both the TEG η_{te} and power densities can be increased by improving the material ZT or increasing the temperature difference ΔT between the TEG hot- and cold-side surfaces. Since the late 1990s, the ZT of thermoelectric materials has been improved significantly through several approaches, including low-dimensional materials such as superlattice thin films, nanocrystalline structures, and nanocomposites [9–14]. Despite significant ZT increases in nanostructured materials, there have been numerous challenges in using these materials for high-temperature TEGs due to their poor thermal stability and low mechanical strength at high temperatures, as well as difficulties in making reliable metal contacts with low contact resistances [15,16]. Several theoretical studies have identified TEGs as a promising approach for CHP applications [17–19]. However, there have been few experimental studies on TEGs for micro-CHP systems, and the majority of them were using bismuth telluride based TEGs that can only operate under hot-side temperature <200 °C with very low efficiency and power density [20–25].

Here we report a micro-CHP system using nanostructured bulk high-temperature TEGs integrated in a gas-fired combination boiler that provides both space heating and domestic hot water (shown in Fig. 1). The TEG produces an ultra-high electrical power density greater than 2 W·cm^{-2} under the ΔT of 500 °C. In addition, it should be pointed out that the TEG is implemented directly in the ultrahigh-temperature combustion gas close to the boiler burner and thus harnesses the wasted exergy in the boiler, which is essentially different from the conventional method of waste heat recovery involving the TEG further down the exhaust stream.

2. Fabrication of high-power-density TEGs

The TEG is fabricated using the nanostructured bulk half-Heusler alloys with a peak ZT of 1.0 at 500 °C (n-type) and 0.9 at 700 °C (p-type), which are 25% and 80% higher than their non-nanostructured bulk counterparts due to the large reduction in thermal conductivity as a result of nanostructuring [26–30]. In addition, the nanostructured half-Heuslers have comparable thermal stability and improved mechanical strength compared to their bulk counterparts in the operating temperature range up to 600 °C [31].

The bonding between the thermoelectric materials and metal conductors is the most important process in TEG fabrication because of the requirement for high bonding strength and low electric contact resistances. Here the n-type and p-type half-Heusler elements ($1.8 \times 1.8 \times 2$ mm^3) were directly brazed to a thin copper plate of 0.3 mm thickness at 825 °C in vacuum using the silver and copper based brazing alloy (Incusil®-ABA™), which enables the TEG to operate reliably at hot-side temperatures up to 600 °C. This simplified metal contact processing yields not only ultra low contact resistivity of ~1 μΩ·cm^2 but also very high bonding strength of 40 MPa [32]. The thermoelectric device consisting of 60 n- and 60