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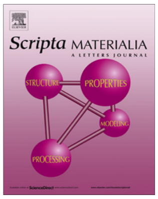

Viewpoint Paper

Thermoelectric topping cycles with scalable design and temperature dependent material properties

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ABSTRACT

Analysis and optimization of topping thermoelectric generators with bottoming Rankine cycle is presented. Interface temperature between the two cycles is optimized for fuel efficiency. It is shown that the topping thermoelectric generator may increase the system efficiency by 6% for a coal-fired power plant with approximately 0.2–0.3 \$/W in material cost. The topping cycle can be a viable large scale application of thermoelectric generators since peak ZT of the material can be optimized in a narrow temperature range without cascading.

1. Introduction

It is remarkable that, since 1961 [1], a very early success of the thermoelectric (TE) power generator was a high temperature (~1000 °C) application enabling spacecraft powering systems by an auxiliary nuclear reaction heat source called the radioisotope thermoelectric generator (RTG). The RTG materials first used lead telluride (PbTe) and later switched to silicon germanium (SiGe). On the other side of the extreme temperature, the success of multistage thermoelectric coolers in refrigeration (~−140 °C in vacuum) [2] has been well known. These historical facts show that thermoelectric power generators are scalable in a wide range of temperatures.

In industrial power generation, coal fired midscale power plants have provided 50.4% of the electricity supply in the U.S. [3]. Natural gas is typically used for micro-grids or on-site power generation, while the penetration of renewable energy sources remains a much lower fraction. Renewable resources are hindered by capital cost, intermittency, and seasonal swings [4,5]. The energy conversion efficiency of Rankine cycle technology alone is around 40%, which has a reasonable economic return on investment. However, higher efficiency is also critical for conserving natural resources [6] as well as for the reduction of CO_2 equivalent gas emissions in preventing global warming. The physics behind the proposed approach is based on maximizing exergy (useful energy) in a large temperature gap between the fuel burning temperature and the gas temperature coming into the turbine. A state-of-the-art combined Brayton–Rankine cycle uses a wider temperature span and generates power with more than 55% efficiency. However, the gas turbine system is significantly complex and impacted by surface to volume ratio; hence, the system will not be scalable to smaller than 100s MW power plants.

Thermoelectric generation is highly scalable by arraying solid-state modules to cover any size heat source and generate power from 1 W to more than 100s MW. These are very favorable features mitigating the higher side of the unused temperature in fuel burning power generation systems. In a previous work, we investigated the TE topping cycle with the Rankine cycle [7]. Fig. 1 demonstrates the system performance with the topping TE and indicates an optimum steam temperature for maximizing total output power. Another team investigated the TE topping Brayton cycle [8], but here we focus more on the smaller scale power plants that are desirable for distributed and smart grid application.

One can increase the total efficiency even further by utilizing TE for waste heat recovery [9,10] from exhaust gas that comes from internal combustion engines, etc. The waste heat recovery can coexist with the topping cycle without interference. We will compare these in performance and cost effectiveness.

Fig. 2 illustrates the system schematic of a current state-of-the-art 520 MW class power plant unit [11]. To enable a realistic and practical evaluation, Silaen et al. [12] analyzed the fluid-dynamic behavior of the gas in the furnace and solved the conjugate heat transport using computational thermo-fluid

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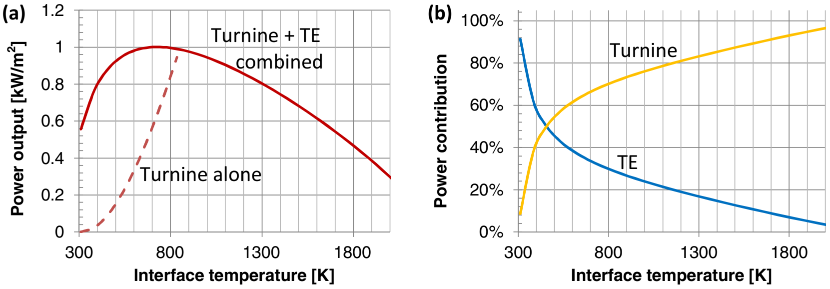

Fig. 1. (a) Power output of the combined system as a function of the interface temperature with broken curve shows the turbine only power output with is limited by the steam temperature below ~800 K for cost effective applications, (b) TE and steam turbine contributions for the system power output. TE module assumes a constant figure-of-merit $Z = 6.67e{-}4$ for the entire temperature range of investigation, and the TE modules are designed to be optimized for maximum power output. The interface temperature assumes the steam temperature at boiler for a steam turbine (Rankine cycle).

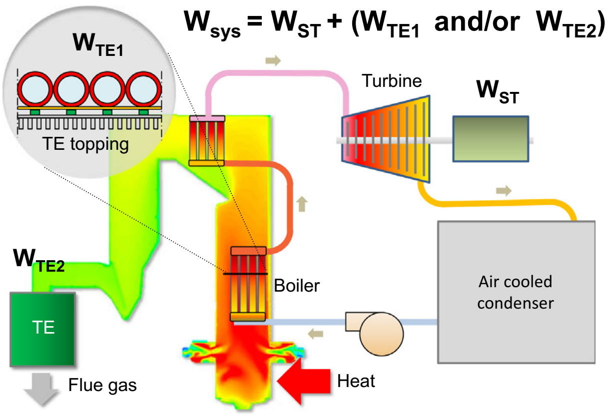

Fig. 2. System diagram of TE topping cycle W_{TE1} and flue gas W_{TE2} power generators with a Rankine cycle coal-fired power plant W_{ST} with air cooled condenser. Overall power output is W_{sys} depending on whether the topping cycle or flue gas TE power generator is integrated, or both.

dynamic analysis. With surface area enhancement, the TE modules are designed between the wall of the boiler and the steam tubes. The TE elements are optimized locally for the simulated gas temperature profile, which is graded along the wall height of over 20 m. These basic designs and analyses enable the prediction of a realistic overall efficiency in accordance with temperature–entropy (*T*–*s*) diagram analysis for a complete superheated Rankine cycle.

Considering the scalability of TE in design for temperature and power range, we investigate and optimize the TE generator design for the system efficiency and cost performance in the above specific case of a power plant while considering a constant ZT value as a universal number. Then, we discuss the impact of the real material, which has temperature dependency for three thermoelectric properties.

2. Materials for high temperatures

RTGs typically use silicon germanium (SiGe) alloys. The system-level conversion efficiency for state-of-the-art RTGs is about 6%, with lifetimes in excess of 30 years [1]. We base our analysis on well characterized SiGe material [13,14]. The SiGe used for spacecraft applications can be improved, and its figure-of-merit (ZT) has been increased to ZT = 1 via nanostructuring, which decreases thermal conductivity without substantially changing the electrical properties [15]. Germanium, however, is a less abundant material and is unfortunately not practical for large-scale deployment in power plant applications. The use of SiGe will also slightly limit the highest operating temperature at the hot side of the TE leg. State-of-the-art p-type $Yb_{14}MnSb_{11}$ and n-type $La_{3-x}Te_4$ have demonstrated maximum ZTs in the range of 1.2–1.5 at 1300 K and are being actively pursued by NASA JPL for space applications, but these are not abundant either. If we traded off the performance, nanostructured silicon materials could be considered as they have reasonable ZTs (0.3–0.4) at high temperatures. Given the variability in ZT values as well as the practical material considerations, we use ZT as an adjustable parameter within the practical range described above.

We subsequently investigate the design of the thermoelectric module and the potential parasitic losses. Based on preliminary calculations presented in Ref. [16], the optimum TE leg thickness for the particular boiler described in Section 2 should be approximately 1.3 mm considering the currently available SiGe with 10% fractional area coverage of TE legs inside the module. This will require a metal/semiconductor contact resistivity in the range of 10^{-5} Ω-cm², which has been achieved [17]. Also, thermal parasitic losses need to be considered through the non thermoelement areas via radiation heat transfer and gap material (usually air) heat conduction. Based on Ref. [17], these parasitic losses are less than 10% of the heat conduction through the thermoelement with 10% fractional area coverage. If needed, a partial vacuum ranging 500 Pa or a coating with reduced emissivity by 0.3 may cut down on the loss contribution by less than 2% for each.

3. Optimization of TE design

A typical TE generator consists of n-type and p-type semiconducting materials connected together in series and placed in parallel along the heat flow direction. At the junctions of n- and p-type materials, electronic potential is created in proportion to the temperature difference; hence, an electric current is generated as the circuit closes and eventually generates power at the external load. The power generation is measured by three key properties: Seebeck coefficient (S) [V/K], thermal conductivity (β) [W/mK], and electrical conductivity (σ) [1/Ωm]. The well-known dimensionless figure-of-merit of TE material ZT is defined by

$$\mathrm{ZT} = \left(\frac{\sigma S^2}{\beta}\right) T \tag{1}$$

where, T is the absolute mean temperature of the TE element.

A TE power generation system can be modeled based on a generic thermal equivalent circuit taking into account external finite thermal resistances with the hot and cold reservoirs, as shown in Fig. 3. We introduce a fill factor F, which is the fractional area coverage of a thermoelement per unit substrate area. Due to the abrupt cross sectional area change in heat current flow, it introduces three-dimensional spreading or constriction thermal