D135 Exergy Analysis of Cost Effective Thermoelectric Topping Cycles

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Abstract
We describe an exergy analysis for thermoelectric (TE) generators used as a topping cycle on top of Rankine cycle steam turbines. The TE generators are utilized to effectively convert the available heat at higher temperature than the temperature range of the steam turbine in current power plants. The destroyed exergy flow by adding TE generators is a function of the thermal resistances. The balance between the TE power generation and the available energy for the bottoming cycle needs to be considered. We also investigate the performance per investment cost [W/$] for the topping TE generator and the waste heat recovery TE as a comparison. Higher exergy utilization with the thermal resistance across the boiler wall improves the system efficiency by approximately 6%. Adding the topping cycle results in a relatively better efficiency than significantly lower cost compared to the waste heat recovery of the flue gas of the boiler.

Introduction
Coal fired steam turbines (Rankine cycles) are popular as mid-scale electric power generators. Such generators with hundreds of megawatts of power must be cost effective. Additional uses are for power redundancy in micro-grids and data centers. State-of-the-art steam turbines using superheated steam at high pressure perform at efficiency in the 42% range. For these turbines, the practical steam temperature is limited to about 800 K to prevent mechanical stress failures. This temperature is significantly lower than the hot gas temperature adjacent to the boiler wall which is as high as ~1680 K [1]. This temperature difference has not been utilized and is much larger than the difference between the waste heat, ~453 K, and the ambient temperature, 313 K. We analyze the TE topping cycle and the waste heat recovery by studying the exergy flow and cost effectiveness.

Model
An analytical 1-D model is used for the system level analysis according to [2]. The TE generator is considered as a network of thermal resistances (see Fig. 1a) with additional heat inputs and outputs at the nodes induced by electrical contacts to an electrical load resistance. The thermal resistances at the hot and cold sides represent thermal interface and heat sink, respectively. Generated power in the TE is delivered to an electrical load resistance. The overall thermal resistance of the TE generator should match the thermal resistance of the boiler cylinder wall if we don’t want to change the steam-tube configuration. Otherwise, the amount of heat used to generated steam will change and result in a temperature change in the bottoming cycle. When the TE elements are designed to match the electro-thermal co-optimum for maximum power output [3], the thermal resistance of the TE element should be similar to the sum of the hot side and cold side thermal resistances.

Exergy analysis
Exergy is a measure of the maximum possible work in a process according to [4]. In this particular TE generator system, the exergy per unit area, $E_{\text{w}}$ [W/m²], is found in steady state as the product of the heat flow per unit area and the Carnot efficiency. As shown in Fig. 1, the destroyed exergy flow exits to the right and the delivered exergy is transported downward.

$$q_w - q_{r} = w$$
$$w = \eta_{c}(T_{h} - T_{c})$$
$$- \frac{i'R}{(T_{h} - T_{c})/\eta_{c}}$$

Figure 1. a) 1-D thermal network of a generic TE cycle and b) corresponding exergy flow. Bypass flows shown in blighter color represents the electrical process across the TE element in a closed circuitry with an external load resistor.

The exergy is destroyed in three stages of the system including the thermal contacts, $\psi_{w}$, $\psi_{c}$, and the thermal resistance of the thermoelement, $\psi_{e}$, in the thermal network shown in Fig. 1a). Heat input and output added to the TE element in the center section are induced by the current flow in the closed electrical circuit. The output specific exergy flow, $E_{\text{out}}$ [W/m²], is equal to the electric power output, $w$ [W/m²], which is no longer temperature dependent, and the remaining specific exergy for the bottoming cycle, $E_{\text{waste}}$ [W/m²], are found by Eqs. (1) and (2), respectively.

$$E_{\text{out}} = w$$

and,

$$E_{\text{waste}} = q_{c}(1 - \frac{T_{c}}{T_{s}}) - w$$

where, $q_{c}$ is the waste heat per unit area, $T_{s}$ is the TE cold side temperature, and $T_{c}$ is the interfacial temperature to the bottoming cycle, the steam temperature for the topping cycle. At the maximum power output from the TE generator, $(T_{h} - T_{c})$ is equal to half of $(T_{h} - T_{c})$ where, $T_{c}$ is the source temperature.
Fig. 2 shows the specific exergy flow in a TE topping cycle at the maximum output power versus the thermal resistance ratio, \( \psi/\psi_n \), while the total thermal resistance remains the same. According to Ref. 1, the example case assumes \( \psi/\psi_n = 1 \). The exergy output is essentially constant as it is always designed to be optimum. Since the cold side resistance is small, the destroyed exergy \( \Xi_{dest} \) at the cold side increases as the thermal resistance ratio increases. At a certain point, \( \psi \) begins to dominate the entire heat flow hence the hot and cold side exergy, \( \Xi_{hot} \), \( \Xi_{cold} \), and \( \Xi_{dest} \) decrease. Fig. 3 shows the impact of the figure-of-merit (ZT value) of the TE material. Exergy output increases as the ZT value increases. In contrast, the available heat flow for the next step gradually decreases. In an overall cascade system, increasing the efficiency or taking larger temperature delta for the topping cycle may sacrifice the available energy for the downstream bottoming cycle. This suggests that there is an overall performance tradeoff when ZT value increases and/or the temperature range used for the topping cycle increases.

![Figure 2](image1)

**Figure 2.** Specific exergy flow vs. thermal resistance ratio, \( \psi/\psi_n \), for topping TE. \( T_h=1680 \text{ K} \) and \( T_c=800 \text{ K} \) (steam temperature). TE is always designed for maximum output power with \( ZT \sim 0.7 \) with 10% area coverage of the TE element. The hot and cold side heat transfer coefficients are 738 [W/m²K] and 722 [W/m²K], respectively.

![Figure 3](image2)

**Figure 3.** Specific exergy flow vs. ZT value. The conditions are the same as Fig. 2.

**Cost discussion**

Flue gas waste heat recovery is also an important consideration for exergy conservation. The addition of flue gas waste heat recovery to a topping cycle is almost free of negative impacts in improving the system efficiency except for the increased back pressure due to the heat fins that are applied in the flue gas flow. The cost consideration for both TE cycles then becomes interesting. According to the electro-thermal impedance match with factor of \( \sqrt{1+ZT} \) [3], the higher heat flux results in a higher power density. The relationship is linear since the heat transport changes linearly while the material mass does not change [2]. A larger temperature difference for the high temperature in the topping cycle provides a significantly larger output power per investment cost, [W/$], compared to waste heat recovery. Fig. 4 shows a cost comparison of the TE generators assuming matched TE materials for the temperature range. The cost calculation is based on the assumptions made in Ref. 1. The power output per cost goes against the trend for efficiency relative to the key design parameter for the TE thickness.

![Figure 4](image3)

**Figure 4.** Power per investment cost [W/$] and efficiency vs. designed TE thickness. TP stands for topping cycle and WHR stands for waste heat recovery. TE materials are considered for a nano-enhanced SiGe \( (ZT \sim 0.7) \) for topping cycle and bulk PbTe \( (ZT \sim 1.0) \) to match the temperature range. 10% area coverage for the TE element is assumed.

**Conclusions**

We analyzed exergy flow based on a 1-D analytic model for the TE topping cycle on a Rankine cycle steam turbine. The analysis showed that the state-of-the-art superheated steam turbine systems with an efficiency of 42% still have room to improve the efficiency by 6% by adding a TE topping cycle with a \( ZT \sim 0.7 \) and 10% if both the topping cycle TE generator and the waste heat recovery TE generator \( (ZT \sim 1) \) are both utilized. Due to the uniqueness of the TE generators, higher heat flux is more cost effective and the topping cycle can provide a power output per investment cost [W/$] range similar to that of the steam turbine. Increasing the efficiency of the topping cycle TE generator can provide a benefit in harvesting higher exergy but it also sacrifices downstream power generation. The optimum approach therefore, is to strike a balance between the output power and the efficiency.

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**References**