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A modeling comparison between a two-stage and three-stage cascaded thermoelectric generator

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HIGHLIGHTS

- Performance comparison between two-stage and three-stage cascaded TEGs.
- Depiction of the thermal resistance network to assist in quantifying heat loss.
- Evaluation of factors affecting the power and efficiency of cascaded TEGs.
- Effect of temperature dependent properties and heat loss on the TEG is included.
- The negative effect of the Thomson power rate on TEG performances is captured.

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ABSTRACT

In this work, a comparison between the performance of two- and three-stage cascaded thermoelectric generator (TEG) devices is analyzed based on a prescribed maximum hot side temperature of 973 K, an imposed maximum heat input of 505 W, and a fixed cold side temperature of 473 K. Half-Heusler is used as a thermoelectric (TE) material in the top higher temperature stage and skutterudite as a TE in the bottom lower temperature stage for the two-stage structure. Lead telluride is added in the middle stage to form the three-stage structure. Based on the prescribed constraints, the two-stage cascaded TEG is found to produce a power output of 42 W with an efficiency of 8.3%. The three-stage cascaded TEG produces a power output of 51 W with an efficiency of 10.2%. The three-stage cascaded TEG produces 21% more power than the two-stage does; however, if the system complexity, mechanical robustness, manufacturability, and/or cost of three-stage cascaded TEG outweigh the 21% percent power production increase, the two-stage TEG could be preferable.

1. Introduction

Clean and efficient energy is currently in demand as the cost of energy and concerns of carbon-emission are increasing. Thermoelectric generation is a promising technology that converts waste heat into electricity in an efficient and clean way [3]. Most current commercial TEGs suffer from a low power output and efficiency due to TE materials not being able to sustain high operating temperatures, low figure of merit (ZT) values, and TE material properties varying with temperature. To increase efficiency and power output, TEGs need to operate at large temperature differences and employ high ZT thermoelectric materials. Various optimized designs of segmented and cascaded TEGs have been proposed in the literature in order to increase the overall power and efficiency of the TEGs [5–9]. Segmented TEGs are designed with different TE materials segmented together such that a TE material with higher ZT at high temperature is segmented with a different material with higher ZT at low temperature. However, TE materials with dissimilar compatibility factors cannot be combined by segmentation into an efficient thermoelectric generator because of

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Nomenclature

A	Area (m^2)
I	Electrical current (A)
K	Thermal conductance (WK^{-1})
k	Thermal conductivity ($Wm^{-1}K^{-1}$)
L	Length (m)
N	Number of pairs of p-type and n-type semiconductors in the top stage
M	Number of pairs of p-type and n-type semiconductors in the mid stage
P	Number of pairs of p-type and n-type semiconductors in the bottom stage, Power output (W)
Q	Heat flow rate (W)
R	Electrical resistance (Ω)
T	Temperature (K)
x	Coordinate
ZT	Figure of merit of a thermoelectric element
Greek Letters	
α	Seebeck Coefficient (VK^{-1})
Δ	Difference
δ	Thickness (m)
η	Efficiency
ρ	Electrical resistivity (Ωm)
Subscripts	
c	Cold junction
cd	Conduction
H	Heat supplied from the heat source
h	Hot junction
L	Heat sink
n	n-type semiconductor leg
opt	Optimal
out	Output
p	p-type semiconductor leg
$m1$	First intermediate temperature
$m2$	Second intermediate temperature
rd	Radiation
teg	thermoelectric generator device
tot	Total

constraints imposed on the relative current density [10]. One way to solve the compatibility issue is to employ cascaded TEGs that stack more than one TEG stage [13]. Each stage of the cascaded TEG can employ a different material based on the material properties. The cascaded structure allows optimization of ZT over the entire temperature gradient and allows the materials to operate with different current densities. This results in a higher effective ZT for the thermoelectric module and thus higher electrical generation efficiency.

Detailed modeling of the performances of cascaded TEGs allows rapid design iterations for optimum cascaded TEGs in a cost-effective manner. Although the concept and design of cascaded TEGs have been introduced before [14–16], rigorous analytical models for cascaded TEGs still lack. For an effective TEG design, a large number of factors must be taken into account including geometric parameters, temperature dependence of TE material properties, heat loss, and thermal and electrical contact resistances [17]. In this work, a detailed analysis and comparison between the performance of a two-stage and a three-stage cascaded TEG is presented. Both of the studied cascaded TEG are imposed with a maximum limit of 505 W flowing into the TEG, a maximum hot side temperature of 973 K, and a cold side temperature of 473 K. Temperature dependent TE material properties, Thomson effect along with the heat loss attributable to radiation and conduction are considered in this analysis. The two-stage cascaded TEG is found to possess an efficiency of 8.3% and to output a power of 42 W. The three-stage cascaded TEG possesses an efficiency of 10.2%, producing a power output of 51 W. This direct comparison may provide useful guidance for future design of cascade TEGs.

2. Method

The expressions describing the heat absorbed on the hot side and cold side of both the two-stage and three-stage cascaded TEGs, are presented. The two-stage cascaded TEG uses half-Heusler in the top hotter stage and skutterudite in the bottom stage, whereas the three-stage cascaded structure has the same top and bottom stage, and an additional middle stage containing lead telluride. Fig. 1 highlights the temperature ranges for the TE materials' ZT used in the analysis, including half-Heusler [1,2], lead telluride [4], and skutterudite [11,12] as a function of temperature. Half-Heulser and skutterudite are chosen respectively as thermoelectric materials for the top hot side and bottom cold side as each possesses relatively high ZT values and are mechanically stable in the corresponding temperature range. Although the ZT of skutterudite is higher than of half-Heusler, it is not as stable as half-Heusler at high temperatures. Skutterudite is therefore not considered as a TE material in the top layer of both the two-stage and three-stage cascaded TEGs. Although lead telluride has a higher ZT value at high temperature than that of half-Heusler, half-Heusler is more stable at high operating temperatures [18]. In addition, evaporation of tellurium at elevated temperatures causes instability of the material's thermoelectric properties [19]. Lead telluride is therefore employed as the intermediate thermoelectric material. To increase the overall ZT of each of the cascaded TEG, this analysis aims to operate each stage between the temperature ranges depicted in Fig. 1 b for the three-stage cascaded TEG and Fig. 1 c for the two-stage cascaded TEG. Both cascaded structures are subjected to the same boundary conditions of a maximum hot side temperature of 973 K, a fixed cold side temperature of 473 K, and heat input close to but less than 505 W. Based on the prescribed conditions, an evaluation is performed to determine the increases in output and efficiency obtained by adding the third stage.

2.1. Thermal resistance network

The thermal resistance network assists in quantifying the major thermal resistances occurring within the cascaded TEGs. From the thermal resistance network shown in Fig. 2, equations describing the radiative and conduction heat loss within the TEG are established. The convection losses are negligible due to a low Rayleigh number [20].

In order to express the geometry of the TEG air gap, a ratio introduced in Ref. [21], frequently described as the packing fraction, is utilized: