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A regenerative concept for thermoelectric power generation

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HIGHLIGHTS

- A regenerative concept for TE based waste heat recovery systems is proposed.
- Similar power output to high-T TEGs is achieved using only low-T TE materials.
- Low-cost, reliable, and available low-T TEMs can be used for high-T applications.

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ABSTRACT

This paper presents a regenerative concept for thermoelectric (TE) based waste heat recovery systems called thermoelectric generators (TEGs). TEG is usually a modified heat exchanger with the addition of thermoelectric modules (TEMs) to recover waste heat for power generation. To utilize heat from high temperature heat sources, current researches have largely been focused on the development of high temperature TE materials. In this study, we describe a regeneration concept in which a precooler is used to lower the temperature of the hot gas and at the same time regenerate hot air from the cold air supply for Bi_2Te_3-based TEGs, avoiding the use of high-temperature thermoelectric materials. It is found that the regenerative TEGs can achieve a similar power output compared with TEGs using high temperature TE materials such as filled-skutterudites (combined filled skutterudites and Bi_2Te_3 TE materials) through obtaining a higher heat scavenging rate. Thus, the regenerative TEGs also have a similar absolute efficiency, defined according to the total available enthalpy from the hot gas. This could represent a paradigm shift in the TEG research and development, that much lower-cost, reliable, and readily available TE materials and modules can be used for high temperature applications, and will ultimately enable wide spread deployment of TEGs for real world waste heat recovery applications.

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1. Introduction

The increasing demands on energy and the concerns on fuel shortage and carbon emission have drawn attentions to the recovery of waste heat, which is abundant from vehicle exhaust to power plants and industrial furnaces. These waste heat sources may vary within a wide temperature range from just above the room temperature to over 1000 °C. Among methods of waste heat recovery, thermoelectric generators (TEGs) are featured with direct conversion to electricity, high reliability without moving parts or special working fluids, and no vibration or noise emission. Over decades of research and development, a wide spectrum of thermoelectric materials, including more recent developments of nanostructured materials have been discovered and synthesized to achieve high figure-of-merit ZT, defined as $\alpha^2\sigma T/k$ with α, σ, k, and T being the Seebeck coefficient, electrical conductivity, thermal conductivity, and absolute temperature, respectively, for a wide temperature range from sub-room-temperature to over 1000 °C [1–5].

Numerous efforts have been devoted into developing TEG applications [6–20], mostly focused on but not limited to engine and industrial waste heat recovery. Design calculations were carried out to improve the performance of power output/efficiency, reliability, and costs, and also evaluate the trade-off among these parameters. Numerical modeling made it possible to investigate these factors in a fast and economical manner [21–29]. Many research efforts have been dedicated to the development of high temperature TE materials [2,3,30–34] for converting high temperature heat sources to power, and achieving high ZT [34,35]. Up till now, however, there are no reliable high temperature TE modules made commercially available. The large thermal stress of materials at high temperature and chemical instability, which often result in the requirements of using inert gas or vacuum encapsulation [36]

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in the TE module and the TEG, are just some of the main barriers of using these materials. Although there are high temperature TEG demonstrations [6,8,14,15,17,19,20,37] and designs particularly addressing reliability or costs [10,38], in general, implementing a high temperature TEG poses much greater engineering challenges. On the other hand, low temperature TEGs are much more reliable and ready to use [22,35,39,40].

In addition to efficiency and reliability, the cost-performance analysis is also key for the commercial feasibility of a TEG. Cost-effective analyses have been carried out to illustrate the competitiveness of TEGs to improve fuel efficiency [41,42], and cost-per-watt [43] is often used for TEGs evaluation. It was also found that the commercial barriers of using high-temperature TE material are largely the system costs [44,45]. However, lacking sufficient data on the costs of manufacturing high-temperature modules and high temperature TEGs, accurate system cost estimations are yet to be conducted. It is also noted that the cost of materials usually accounts for about 10% of a high-temperature TEG, indicating the choice or processing of materials are not the promising direction for lowering the overall TEG cost though some reductions can be made [44]. The transient performance [46], electrical connection [47], etc. are also important factors for the TEG engineering realization. However, it is only meaningful to consider these factors after the cost-effectiveness and reliability proven to be acceptable by the market.

The concept of regeneration has been accepted in varieties of thermal systems, including Stirling engines, absorption cooling system, and especially combined turbine cycles. Taking advantage of high performance heat exchangers, regeneration produces additional lower temperature heat sources and thus improves the efficiency by a noticeable amount. However, this useful and practical concept has yet to be applied or investigated for thermoelectric power generation. In this work we introduced the regeneration concept to the area of TEG and proposed the regenerative thermoelectric generator (R-TEG) for recovering power from high temperature waste heat sources, using entirely low temperature TE materials to circumvent the complications of manufacturing a high temperature TEG.

The proposed R-TEG first cools the hot gas to a temperature acceptable by low temperature TE modules, and simultaneously raises the temperature of a stream of cold ambient air. Both the cooled hot gas and the heated air are then fed into the TEGs that use low temperature TEMs (Bi_2Te_3 modules are used in this study). Two types of regeneration designs are studied using the previously established numerical methods [48,49] and the optimization algorithm [50]. For comparison, the power outputs from a high temperature TEG using combined filled-skutterudite and Bi_2Te_3 TEMs (referred to as high-T TEG in this work) are computed. It is found that the regenerative TEG can achieve similar performance as the high-T TEG. For waste heat recovery, the goal is to maximize the power output with a given amount of waste heat source. The absolute efficiency, defined as ratio of the power output and the available enthalpy from the heat source, is an indicator of the TEG performance. Therefore, the regenerative TEGs have a similar absolute efficiency compared with the ones using high temperature TEMs. A cost analysis of R-TEGs is also performed. The reason for the high performance of the R-TEG is analyzed, and is proven to be consistent with the existing TE generation theory. Given the tremendous benefits of using low temperature TEMs for the R-TEG, including much lower-cost, reliability, and availability, the development of R-TEGs will represent a paradigm shift in the TEG research and development, and will ultimately enable the wide spread deployment of TEGs for real world waste heat recovery applications.

2. Description of R-TEG

The R-TEG is designed based on a counter flow heat exchanger as shown in the gas flow chart in Fig. 1. We assume the waste heat source is hot gas (air) at 800 K with a mass flow rate of 0.1 kg/s, and the room temperature air (300 K) is the coolant. The hot gas first enters a gas phase heat exchanger called precooler, to cool to a temperature that is acceptable for Bi_2Te_3 modules. In this work, we limit the hot side junction temperature of the Bi_2Te_3 TEMs to be lower than 550 K [40]. The cooled hot air then enters a Bi_2Te_3-based TEG labeled as sub-TEG1 in Fig. 1.

For comparison, we also compute and optimize conventional high-T TEGs, where filled-skutterudite modules are used in the higher temperature sections and Bi_2Te_3 modules at the lower temperature sections. The hot side junction temperatures of Bi_2Te_3 modules in these high-T TEGs are also kept below 550 K. The detailed parameters of the two types of TEMs are taken from Ref. [49].

In our R-TEG design, the cold air that is used to cool the hot air in the precooler comes from TEG1 in order to recycle (regenerate) more heat as shown in Fig. 1. The regenerated hot air is then fed into a second Bi_2Te_3-based TEG (sub-TEG2) to produce more power. The amount of the cold air used for the precooler is chosen such that the temperature of the output of the warmed cold air reaches the limit for being used in sub-TEG 2, i.e., the same as the inlet temperature for sub-TEG 1. The size and the cold air supply for sub-TEG 2 are thus proportional to those of the sub-TEG 1 according to the mass flow rate of the regenerated hot air.

A second R-TEG design is illustrated in Fig. 2. Instead of using a fraction of the cold air from sub-TEG1 for the precooler, the regenerated air continuously flows in a closed loop as shown in Fig. 2. One of the advantages of using the closed loop is that other types of heat carrying fluid can be used, for example, liquid coolant, to significantly enhance the heat transfer rate, resulting in more power output from sub-TEG 2. However, the calculations below are based on air as the regenerating fluid.

The computational model, materials properties, and optimization method for the TEGs are adapted from previous works [48–51]. The precooler is calculated using the ε-NTU method [52]. For the TEGs, there are three major design parameters used in our study: the heat exchanger area (A_{HE}), the aspect ratio (width/length), and the height of TEC legs (H_{TE}). These are the basic geometric parameters of the heat exchangers and TEMs that govern the heat transfer rate and junction temperature difference, and thereby determine the power output. The aspect ratio of the heat exchanger has less an effect on the power output according to the sensitivity analysis [50]. In additional to the aforementioned parameters, the fill factor of the TEM, i.e. the TE material coverage over the total heat transfer area, is held as constant according to the TEM designs for two materials respectively from previous works [48,49]. Thus, the heat exchanging area and height of TEM legs are the only two dominant parameters of the TEG performance for this study. The width of the heat exchanger channel is selected to be 0.27 m. A_{HE} (=0.27 m × length) and H_{TE} are selected as the optimization factors with upper bounds set at 0.2 m^2 and 8 mm, respectively. In addition to the power output, the heat dissipation rate from the hot gas is another key parameter to be evaluated. The hot side convection coefficient is set to a constant 2700 W/m^2 K based on a typical intermittent corrugated plate heat exchanger [53], and the cold side convection coefficient varies according to Eq. (1) with h_0 = 2300 W/m^2 K. The index 0.35 in Eq. (1) is taken from the regression of a similarly structured heat exchanger [53] according to its dependence on the Reynolds number *Re*.

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