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An overview of cooling of thermoelectric devices

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ABSTRACT

Thermoelectric generators are an environmentally friendly source of electrical power whose applications range from waste heat recovery to conversion of solar energy into electricity. Low conversion efficiencies however inhibit their wide scale deployment. Research into thermoelectrics has therefore primarily focused on improvement of material properties, leading to remarkable progress in the area which has not translated into high performing thermoelectric generators. System level efficiency is significantly dependent on effective thermal management. Heat dissipation mechanisms employed to remove waste heat from the cold side of a thermoelectric device are reviewed in this work. The prevalent methods of cooling thermoelectric devices are categorized and based on published experimental data, their contribution on the overall conversion efficiency of thermoelectric generators is quantified. A broad range of devices from low heat to high thermal flux have been covered in this work and will help guide future endeavors in thermoelectric generator design and testing.

1. Introduction

Compared with conventional electric power generators, thermoelectric generator (TEG) offer many advantages such as reliability, no moving parts and environmentally friendly. TEGs accomplish this by exploiting the thermal energy of electrons (and holes) for the energy conversion between heat and electricity. However wide scale application of TEGs has been hindered by their low productivity, due to low thermal-to-electrical conversion efficiencies (typically $<10\%$) [1–3] limiting their use in specialized military, medical and space fields. Nevertheless, in applications where the thermal energy is abundant or very low cost, as is the case with solar energy or waste heat, TEGs are commercially viable. Two directions have been highlighted for achieving wider applications of thermoelectric devices [4], first is to promote the intrinsic efficiencies of thermoelectric materials and the other is to improve the way TEMs are integrated into electrical power producing units, of which thermal management is an important part. While there is significant work on hot side thermal management of TEMs, focusing on solar energy [5], automotive exhaust [6], and waste heat [7]; cold side thermal management has received less attention. In this paper, we review different methods used to dissipate heat from the cold side of the TEM over a broad range of operating parameters and present their performance parameters.

2. Thermoelectric efficiency

2.1. Theoretical efficiency

The conversion efficiency, η_{TE} is dependent on the temperature difference ΔT and the figure of merit $Z\overline{T}$ (the effective ZT across ΔT) defined as $Z\overline{T} = (S^2T/\rho\kappa)$ and determined by the three main material parameters: the Seebeck coefficient or thermo power $S(\mu V/K)$, the electrical resistivity $\rho(\Omega\, m)$ and the thermal conductivity $\kappa(W/(m\, K))$ [8]. The thermoelectric efficiency is given by:

$$\eta_{TE} = \left(\frac{T_H - T_C}{T_H}\right)\left(\frac{\sqrt{1+Z\overline{T}}-1}{\sqrt{1+Z\overline{T}}\ + (T_C/T_H)}\right) \tag{1}$$

The term in the first parenthesis on the right hand side is the Carnot efficiency of the thermoelectric device operating between hot and cold temperature reservoirs of T_H and T_C respectively. As is evident from Eq. (1), the conversion efficiency depends on the operating temperature and the figure of merit.

The theoretical efficiency of thermoelectric power generators for different $Z\overline{T}$s are shown in Fig. 1 against the efficiencies of other power generation systems [9].

2.2. Figure of merit and efficiency

During the renewed interest in thermoelectrics of the late 1900s the

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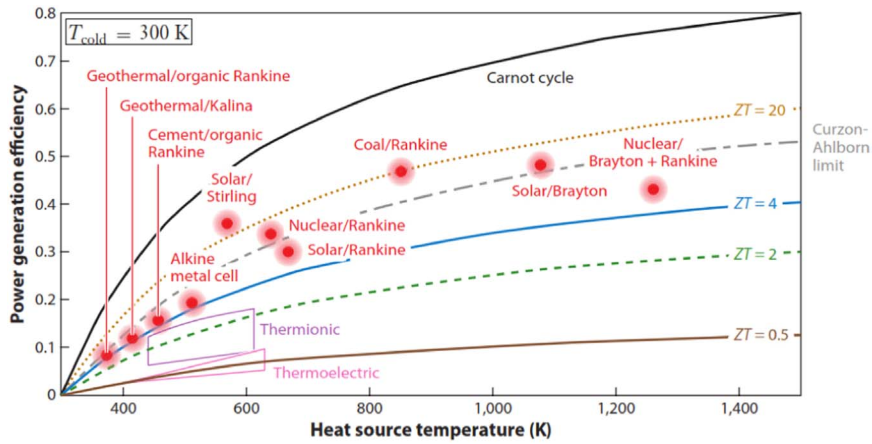

Fig. 1. Comparison of power generation systems. From [9].

figure of merit of available materials was as low as $Z\overline{T} \ll 1$ [10,11] shown in the figure in an enclosed region and these were not competitive against conventional power generators. However because of their noiseless operation, flexibility and form factor they still found niche applications. In search of broader applications fundamental research in thermoelectrics has therefore focused on maximizing the conversion efficiency by developing new, high-efficiency thermoelectric materials with $Z\overline{T} \approx 3-4$ [12,13] which is sufficient to make them competitive against conventional power generation including geothermal and alkaline cells (Fig. 1). In order to accomplish this, the challenges lie in predicting the structures of materials, their electron and phonon band structures and transport properties, as well as in understanding the impact of defects in the materials on transport properties. In a recent effort, Zhang et al. [14] used complex parameter optimization to design module structures that minimize energy losses using Bi2Te3-based alloys and CoSb3-based skutterudites to achieve a peak $Z\overline{T} \approx 1.2$. However, their design resulted in a conversion efficiency of 12% while operating across a temperature difference of 541 degrees and a cold side temperature maintained at 35 °C, comparable to a $Z\overline{T} \approx 2.0$. Similarly, Kraemer et al. [15] achieved a peak efficiency of 9.6% by employing segmented thermoelectric legs, coupled with solar and thermal concentration.

Significant boosts in the peak ZT over the benchmark value of 1 have been reviewed by Z Ren [3] covering many conventional materials such as Bi_2Te_3-based alloys, PbTe, PbSe, SiGe, Mg_2X (X = Si, Ge, Sn), skutterudite, calthrate, Zintl and half-Heusler alloys. These increases have been achieved by tailoring electron transport through nanoscale approach to engineering band structure and tuning phonon transport. Recently the $Z\overline{T}$ of $Bi_{0.5}Sb_{1.5}Te_3$ (bismuth antimony telluride) was increased to 1.86 ± 0.15 at 320 K by reducing lattice thermal conductivity through grain boundary and point-defect scattering targeting high-and-low frequency phonons [16]. Earlier a $Z\overline{T}$ value of 2.2 at 915 K in p-type PbTe endotaxially nanostructured with SrTe was demonstrated by going beyond nanostructing through a panoscopic approach to the scattering of heat-carrying phonons across integrated length scales [17]. An unprecedented $Z\overline{T}$ of 2.6 ± 0.3 at 923 K was reported by Kanatzidis and coworkers for SnSe single crystals and attributed to its ultralow lattice thermal conductivity [18]. Thus several new bulk materials that demonstrate $Z\overline{T} \approx 2-3$ have been identified in literature [13,19,20] and mechanisms for decoupling electron transport from phonon transport in such materials through modification are under investigation for further improvement of the figure of merit.

To understand the contribution of $Z\overline{T}$ on the performance of the thermoelectric device, the ratio of thermoelectric efficiency (Eq. (1)) and Carnot efficiency are plotted against increasing $Z\overline{T}$ in Fig. 2 for temperature differences ranging from 50 to 1000 °C. The curve shows that a thermoelectric device with a $Z\overline{T}$~3 can provide close to 50% of

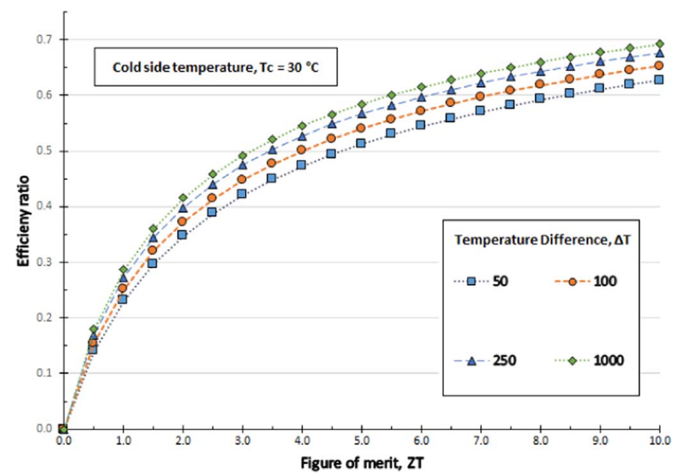

Fig. 2. Ratio of thermoelectric efficiency to Carnot efficiency as a function of the figure of merit for a range of temperature differences.

the efficiency of Carnot cycle (a thermodynamic limit) while operating at room temperature (30 °C) and a temperature difference of 250 °C. It also highlights the limited performance enhancement above a temperature difference of 250 °C, an average increase in efficiency of 0.1% for every 50 °C temperature rise up to a maximum of 1000 °C above room temperature. These next generation thermoelectrics ($Z\overline{T} \approx 2-3$) have already found applications in waste heat recovery in automobiles amongst other uses [21,22]. In addition, thermoelectric are used as coolers to provide cold beverages, as well as in wristwatches and pacemakers by exploiting the very small temperature differences within the body or between a body and the environment [23,24].

2.3. Thermal dependence of efficiency

While the advancement in materials development is encouraging, the budding range of materials and the reports of ascending $Z\overline{T}$s conceal the fundamental challenges of employing these materials in energy conversion on an appreciable scale. Despite these promising results, the efficiency gains at device level has yet to be demonstrated. For example the theoretical solar-to-electricity efficiency of Si-Ge alloys operated at a temperature of 1000 K is 12% [25] compared to experimental findings of efficiencies <1% [26] for conversion of concentrated solar radiation by directly irradiated TE modules operated at 900 K on the hot side. Studies reveal that with high-temperature TEMs 60% of the incident solar radiation is lost due to reradiation and only 20% is available for electricity conversion [27]. Another aspect is the variation in $Z\overline{T}$ with increase in temperature, which has been