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Radiant heat recovery by thermoelectric generators: A theoretical case-study on hot steel casting

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ABSTRACT

We present a detailed numerical analysis to quantify the power generation performance of a thermoelectric module in radiant heat recovery application. Due to the large temperature difference typically involved in such a system, temperature-dependent material properties of thermoelectric elements are taken into account for accurate performance prediction by employing an iterative algorithm based on the one-dimensional finite element method. Careful analysis on the radiation heat transfer with optical parameters such as surface emissivity and view factor is performed to precisely quantify the heat input to the thermoelectric system. Parasitic heat losses such as air convection loss at the hot surface and conduction through the substrates and gap fillers are also taken into account to analyze their impacts on the power output. A case study on the radiant waste heat recovery from hot steel casting slabs in steel industry is discussed in detail to theoretically estimate the power output performances and optimize the module design. We find that a power density as high as ~1.5 kW/m^2 and a system efficiency as high as ~4.6% can be achieved at a 2 m distance from the 1200 K hot steel slab using the state-of-the-art Bi_2Te_3 alloys with a relatively small leg thickness of 3 mm and a 20% fill factor. This optimal design with small form factors ensures a reduced material cost while keeping the power output near the maximum, so that an estimated power cost remains as low as ~0.2 $/Watt.

1. Introduction

With the demand of electricity growing rapidly over the world, technologies for energy efficiency are attracting a lot of attention. More than 60% of energy generated in the United States is wasted mostly in the form of heat [1]. Thermoelectric (TE) energy conversion has drawn great attention recently as a viable technology that can directly convert waste heat into electricity, thereby enhancing the energy efficiency. Thermoelectric energy conversion has been widely used in various applications such as radioisotope thermoelectric generators (RTG) for deep space missions [2], remote power generation for unmanned systems [3], vehicle exhaust waste heat recovery [4], autonomous sensors on the human body [5,6] and waste heat recovery from proton exchange membrane fuel cells [7]. Thermoelectrics has the potential to contribute towards distributed sensor networks enabling automation as well [8].

Over the last couple of decades, exceptional advancements have been made in the fundamental understanding of heat and charge transport in thermoelectric materials as well as in improving existing materials and inventing new materials. There are several excellent reviews on the recent advances in thermoelectric materials [9–12]. The efficiency of a thermoelectric material is determined by the dimensionless figure-of-merit ZT defined as

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

where σ is the electrical conductivity, S is the Seebeck coefficient, k is the thermal conductivity, and T is the absolute temperature. The numerator, σS^2, is called the power factor, which is determined by the electron transport in the material, while the thermal conductivity in the denominator is mostly determined by phonon transport. Recently, nanostructuring has been proven as an effective strategy for suppressing the thermal conductivity without reducing the power factor much to enhance ZT. The ZT values of p-type and n-type Bi_2Te_3 alloys have been improved to 1.4 and 1.0, respectively, by nanostructuring, which are among the best ZT values at low temperatures (300–400 K) up to date [13,14]. There have also been fundamental studies about suppressing the thermal conductivity by creating 'patterned disorders' in silicon and

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Nomenclature

A	area covered by TE modules
A_{leg}	cross-sectional area of a TE element
A_n	cross-sectional area of an n-type TE element
A_p	cross-sectional area of a p-type TE element
A_{total}	total area of a TE module
Ci	coefficient of radiation from the i-th surface
Ebi	blackbody emissive power from the i-th surface
F	fill factor of TE module
F_{rad}	radiation shape factor
h_{conv}	convective heat transfer coefficient
I	electric current
J_i	radiosity of the i-th surface
K_i	thermal conductance of the i-th segment
k	thermal conductivity
k_{filler}	thermal conductivity of filler
k_i	thermal conductivity of the i-th segment
L	distance between hot slab and TE module
L_{leg}	thickness of TE element
N	number of segments in a TE element
N_{pair}	number of TE element pairs
Q_{conv}	convective heat loss from the hot side of TE module
$Q_{\text{in,total}}$	total radiative heat input to TE module after heat losses
$Q_{in,n}$	heat input to an n-type TE element
$Q_{in,p}$	heat input to a p-type TE element
Q_{J_i}	rate of heat transfer by Joule heating coming into the i-th node
Q_{K_i}	rate of heat transfer by conduction from the $(i-1)$-th node to the i-th node
Q_{lateral}	lateral heat exchange inside the hot plate between adjacent n-type and p-type TE elements
Q_{P_i}	rate of heat transfer by Peltier effect going out of the i-th node
$Q_{\text{rad,in}}$	radiative heat input to TE module
$Q_{\text{rad,out}}$	radiative heat loss from the hot side of TE module
R_c	contact resistance per one side of TE element
R_{elec}	electrode resistance per one side of TE element
R_i	electrical resistance of the i-th segment
R_{int}	internal resistance of a TE element
R_L	load resistance
S	seebeck coefficient
S_i	seebeck coefficient of the i-th segment
T	absolute temperature
T_{amb}	ambient temperature
T_{bot}	bottom temperature of TE module
T_C	cold-side temperature of TE element
T_H	hot-side temperature of TE element
T_i	temperature of the i-th segment
T_s	surface temperature of heat source
T_{top}	temperature of the top surface (or heat absorber) of TE module
V_{OC_i}	open-circuit voltage from the i-th segment
w	slab width
ZT	thermoelectric figure of merit
ε_i	emissivity of the i-th surface
σ	electrical conductivity
σ_i	electrical conductivity of the i-th segment
σ_{rad}	the Stefan-Boltzmann constant
ψ_C	heat transfer coefficient of the cold plate including the heat sink in TE module
ψ_H	heat transfer coefficient of the hot plate in TE module

nanocomposites [15,16]. Recent studies showed that band convergence and ultra-low thermal conductivities in rhombohedral GeTe [17] and SnSe [18] have made them excellent thermoelectric materials with ZT above 2.0 in the mid-temperature range (600–1000 K).

One of the recently emerging applications for thermoelectric power generation is utilizing radiant heat sources such as concentrated solar radiation [19] and hot steel slabs in steel casting processes [20]. Recently, a peak power density of 211 kW/m^2 with a system efficiency of 7.4% has been demonstrated for a concentrating solar thermoelectric generator made of segmented thermoelectric elements in a high vacuum operation [21]. This experimental result as well as the modeling study on the design optimization of solar thermoelectric modules [22] showed that the material cost per generated peak power could be lower than 0.05 $/Watt, potentially beating the power cost of the-state-of-the-art photovoltaic systems. Reversely, a TE module can be used to measure solar irradiation intensity [23].

The Steel manufacturing process in the industry requires huge quantities of resources in terms of electrical power [24]. The autonomous operation of the processing lines, e.g. hot rolling mills or continuous casting lines, requires hundreds of sensors like hot metal

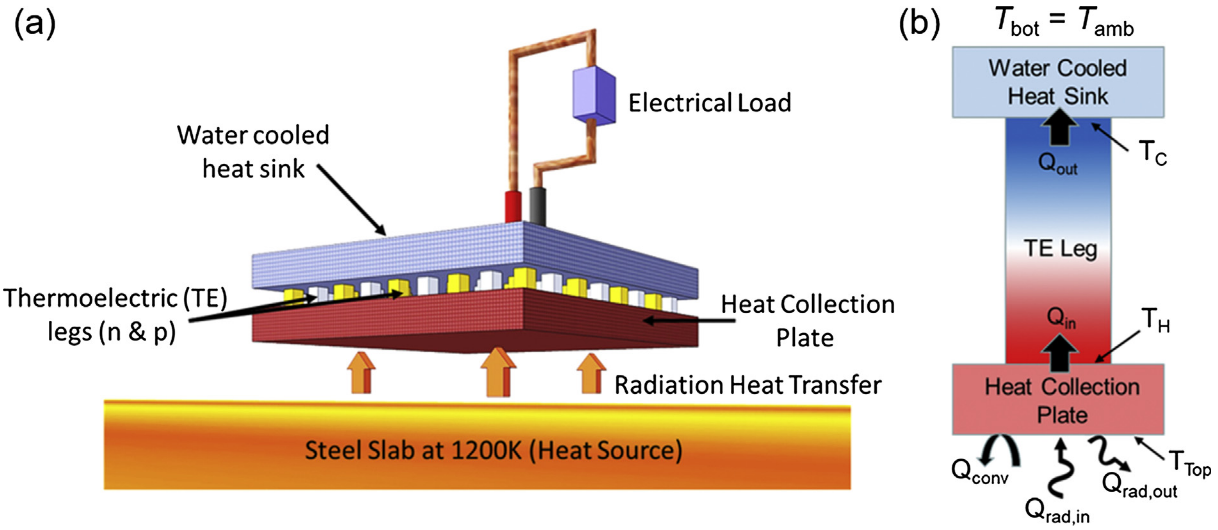

Fig. 1. (a) Schematic of the thermoelectric module suspended over the radiating steel slab. (b) Heat transfer and boundary temperatures in a radiant heat recovery thermoelectric system. Only one TE leg is shown in this schematic.