Energy Conversion and Management 168 (2018) 85–97

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Thermoelectric device multi-objective optimization using a simultaneous TEG and TEC characterization

Trevor Hocksun Kwan[a,*], Xiaofeng Wu[b], Qinghe Yao[a]

[a] School of Engineering, Sun Yat-Sen University, China
[b] School of AMME, University of Sydney, Australia

ARTICLE INFO

Keywords:
Thermoelectric device
TEG
TEC
Multi-objective optimization
NSGA-II

ABSTRACT

The thermoelectric (TE) device enables a conversion interface between the heat transfer and the electricity domain. Specifically, it can operate bi-directionally – Heat can be converted to electricity via the thermoelectric generator (TEG) effect and conversely, electricity can be converted to heat via the thermoelectric cooling (TEC) effect. As to date, most publications deal with the optimization of the TE device either in terms of the TEG performance or in terms of the TEC performance. This paper brings the two design approaches together to form a multi-objective optimization of the TE device. By performing such an optimization, the relationships between the TEG and TEC performance criterion are better established with key factors including any potential trade-off situations and possibilities for optimal design towards both objectives. Moreover, the key parameters that have the strongest influence on these criteria and the related trends are identified. Optimization results indicate that there is a strong correlation between the TEG performance and system mass but the correlation is less effective from the TEC perspective. On the other hand, the constraint requirements on the TEG design is found to have strong influence on the optimality of the TEC solutions.

1. Introduction

The emission of pollutants such as CO_x, NO_x and SO_2 by fossil fuels and their non-renewable nature have raised many concerns and motivated researchers and the industry to develop cleaner and more sustainable technologies. The thermoelectric (TE) device is a potential alternative technology who can generate electricity from a temperature gradient via the Seebeck effect (often also known as the thermoelectric generator (TEG) effect). The TE device can also generate a temperature gradient (hence pump heat power from the cold side to the hot side and vice versa) if an electric current is applied. Operation in such a mode is based on the Peltier effect and is often known as the thermoelectric cooling (TEC) effect.

In comparison to other heating or cooling methods, the TE device is especially recognized in literature in that it is a robust, clean and noiseless electric power generator which does not require any active moving parts [1–3]. Typically, it is used to enhance the cooling capability of conventionally active cooling systems (liquid or air) by enabling waste heat recovery or adding a degree of freedom to the cooling/heating capability.

In terms of the TEG mode, applications include the recovery of waste heat from automotive exhaust systems [4,5], the solar thermoelectric hybrid system [6–9], hypersonic engines [10] and as a cooling system for fuel cells [11–13]. Performance via the Seebeck effect is generally characterized by the thermocouple material characteristics and is quantified by using the ZT parameter where $ZT = \frac{\alpha^2\sigma}{\lambda}$. Here, α is the Seebeck coefficient, σ is the electrical conductivity and λ is the thermal conductivity. A larger value of ZT represents better Seebeck effect performance, therefore, research in the thermoelectric material field is committed to increase α, σ while minimizing σ [2,14,15]. In addition to materials research, the geometric design of the thermocouples, number of thermocouples and the TE device deign itself is also found to have significant impacts on the Seebeck performance [16–18]. For instance, the multi-objective optimization of the TEG in terms of the aforementioned parameters has been presented in various publications such as Refs. [17,19]. Exergy analysis of the TEG device is also popularly considered with example references being that of Refs. [10,20]. Other publications also deal with the electronics aspect of the TEG where Ref. [21] deals with the side effects of mismatch between multiple TE devices connected in series or parallel. The small signal model of the TEG was also proposed recently in Ref. [22] where it extended the DC model of the TEG into the dynamic regimes.

In terms of the TEC mode, applications include the active cooling of photovoltaic (PV) cells [23], power electronic switches [24], high

* Corresponding authors.
E-mail addresses: kwanth@mail.sysu.edu.au (T.H. Kwan), xiaofeng.wu@sydney.edu.au (X. Wu), yaoqhe@mail.sysu.edu.cn (Q. Yao).

https://doi.org/10.1016/j.enconman.2018.04.108
Received 1 December 2017; Received in revised form 28 March 2018; Accepted 28 April 2018
0196-8904/

Nomenclature

α	seebeck co-efficient (V/K)
σ	electrical conductivity (S/m)
λ	thermal conductivity (W/(m K))
ε	surface emissivity
κ	convection co-efficient (W/(m^2 K))
T	temperature at a particular surface (K)
i	current through a single series string of TE modules (A)
i_{TEC}	TEC operating current (A)
$V_{oc(TEG)}$	open circuit voltage of the TEG (V)
$I_{sc(TEG)}$	short circuit current of the TEG (A)
I^*_{TEG}	the quantity of current flowing through the TEG which obtains the optimal TEG power output (A)
r_{TE}	internal electrical resistance of a single thermocouple of the TE (Ω)
R_{TE}	total internal electrical resistance of the TE (Ω)
N	total number of TE modules in the TE device
N_P	number of parallel TE module connections
N_S	number of series TE module connections
n	number of thermocouples in a single TE module
n_t	number of thermocouples in the overall TE device
l	length of thermocouple
A	surface Area (m^2)
L	length of surface
T_H	reservoir temperature of main device
T_L	reservoir temperature of the external environment
Q_H	heat flow from main device to TE device (W)
Q_L	heat flow from TE device to external environment (W)
Q_e	TE device electrical power output (W)
A_R	TEG outlet to inlet area ratio which characterizes the heat sink size
P	the population vector for the NSGA-II Algorithm
R	the offspring population vector for the NSGA-II Algorithm

Subscripts and superscripts

In	refers to properties at the inlet of the TE device
Out	refers to properties at the outlet of the TE device
1	temperature of TE end that is closer to the main device
2	Temperature of TE end that is closer to the external environment
p	p-type type thermopile
n	n-type type thermopile
TEG	refers the variable specifically to the TEG case study.
TEC	refers the variable specifically to the TEC case study.

Abbreviations

COP	Coefficient of Performance
LED	Light Emitting Diode
MPPT	Maximum Power Point Tracking
PEMFC	Proton Exchange Membrane Fuel Cell
SOFC	Solid Oxide Fuel Cell
TE	Thermoelectric
TEG	Thermoelectric Generator
TEC	Thermoelectric Cooler

Numerical constants

$\gamma = 5.670373 \times 10^{-8}$ W m^{-2} K^{-4} The Stefan-Boltzmann Constant

power LEDs [25] and fuel cells [26]. Performance characterization in the TEC mode is often quantified using the co-efficient of performance (COP), the maximum cooling capacity and the maximum allowable operating current in the TEC mode [27]. Similar to the TEG case, performance in the TEC mode is also sensitive to that of the three thermocouple material characteristics α, σ and λ and the thermocouple geometric design and number. Moreover, the genetic algorithm optimization and exergy analysis of the TE device in the TEC perspective also exist respectively in Ref. [23] and Ref. [28]. Alternative to optimization processes, parametric studies of the TEC in terms of the various physical parameters have been conducted in Ref. [27]. Ref. [25] also conducted an experimental study of the TEC for the thermal management of a high powered light emitting diode (LED). The electronic aspect of the TE device in the TEC mode is also dealt with in Ref. [24] for active temperature control. Moreover, Ref. [29] proposed using the supercooling effect in a two-stage TE device where the supercooling effect involves using large amplitude current pulses to improve the transient response in the TEC mode.

As of the state of the art, when the TEG and TEC are considered simultaneously, the system designs usually involve the two modules as separate devices. For instance, a common example involves electrically connecting the TEG module to the TEC module which means the output of the TEG module is used to further pump a temperature differential at the TEC and provide hence an additional cooling effect. This is commonly known as the "thermoelectric generator-thermoelectric cooler combined system" as stated, for example, in Ref. [29]. In this reference, the maximum power point tracking (MPPT) technique on the TEG module is proposed to deliver the maximum possible power to the TEC module, hence maximizing the overall cooling effect. A similar system has also been proposed in Ref. [13] for the cooling of a solid oxide fuel cell (SOFC). On the other hand, adopting the TE device as both being a TEG and TEC is a relatively shallow topic in research where one example that deals with such a matter is Ref. [30]. Here, the TE device is considered for use as a TEC or TEG for space heating in a Mediterranean Climate, depending on the room temperature requirement and the state of the external environment.

This paper intends to further extend the research into the potential of using the TE device as both a TEG and a TEC in a single system. Specifically, the focus in this paper is to perform a multi-objective optimization of the TE device's geometrical design where the objectives consider both the TEG and TEC characterization parameters. For instance, the first objective is to maximize the electrical output of the TE device when heat is applied to its hot side surface. The second objective is then to maximize the cooling capacity of the TE device where the applied current is included as an additional optimizable parameter. Indeed, the overall power versus mass density of the TE device is another important practical parameter and thus is included as another objective for the optimizer. The considered application as the study case is that of a cooling system of a low temperature proton exchange membrane fuel cell (LT-PEMFC). This was chosen because the LT-PEMFC typically has a tight operating temperature range of 60 to 95 degrees Celsius. By conducting such an optimization process, it is possible to establish the relationship of the optimized solutions between TEG and TEC performance. For instance, are there any trade-off relationships between optimizing in the TEG and TEC perspectives? If so, what parameters have the strongest influence in determining such relationships? Alternatively, is it also possible to obtain optimal solutions that are satisfying in terms of both perspectives? This paper aims to answer the aforementioned questions by analyzing the results of the proposed optimization.