Energy Conversion and Management 166 (2018) 337–342

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Influence of leg geometry configuration and contact resistance on the performance of annular thermoelectric generators

A.B. Zhang[a,*], B.L. Wang[b], D.D. Pang[c,*], J.B. Chen[a], J. Wang[a], J.K. Du[a]

[a] Piezoelectric Device Laboratory, School of Mechanical Engineering & Mechanics, Ningbo University, Ningbo 315211, PR China
[b] Centre for Infrastructure Engineering, School of Computing, Engineering and Mathematics, Western Sydney University, Penrith, NSW 2751, Australia
[c] Henan Province Key Laboratory of Water Pollution Control and Rehabilitation Technology, Henan University of Urban Construction, Pingdingshan 467036, PR China

ARTICLE INFO

Keywords:
Annular thermoelectric generator
Leg geometry
Contact resistance
Output power per unit mass

ABSTRACT

Geometry optimization of thermoelectric leg plays an essential role in improving the performance of thermoelectric generator (TEG). In the present study, theoretical analysis of an annular thermoelectric generator (ATEG) is carried out and a general model for investigating the influence of geometry configuration of thermoelectric leg and contact resistance on the output power, output power per unit mass and conversion efficiency is established. The results show that maximum output power per unit mass can be attained only when the cross-section area of thermoelectric leg is constant for the ideal ATEG. The optimized shape parameter is affected by the length of thermoelectric leg if the effect of contact resistance is taken into consideration, however, the calculation error of the performance induced by the variation of shape parameter is very small. In addition, the decrease in maximum conversion efficiency also varies slightly with the optimized shape parameter corresponding to the maximum output power. This study will be very helpful in designing actual ATEG devices.

1. Introduction

Almost 70% of world's energy is wasted as heat which is dissipated in the atmosphere and considered as one of the factors for global warming [1]. Thermoelectric generators (TEGs) can convert thermal energy directly into electrical energy and are ideal for small scale power generation because of their simplicity, no moving components, high reliability, less maintenance cost and environmental friendliness [2,3]. Lots of efforts in developing thermoelectric materials with high figure of merit (*ZT*) have been made, the maximum conversion efficiency of TEGs is still on the order of less than 10%. The relatively low efficiency has been a major factor in limiting their applications in power generation. However, it is unnecessary to consider the cost of the heat input when the TEGs are used to recovery of waste heat, and the low efficiency is not a serious drawback is this application. The primary consideration in recovery of waste heat is to optimize the TEGs to provide maximum output power. The output power and conversion efficiency provide a rough estimation of TEGs performance when they are operating in the power generation mode. In addition, the running cost of TEGs is closely to their conversion efficiency and output power, while the module construction cost is largely determined by the output power per unit mass [4,5]. The output power, output power per unit mass and conversion efficiency of the TEGs are dependent on the length of thermoelectric leg for a given figure of merit, contact resistance properties and temperature difference of operation [6,7]. The theoretical analysis of TEG was carried out and the effect of thermoelectric leg geometry on the output power, irreversibilities, exergy and energy efficiency was studied by Sahin and Yilbas [8] and Lamba and Kaushik [9], and they found that the efficiency can be improved notably when the trapezium shape along leg height is used, but the output power reduces with the increasing or decreasing shape parameter. The influence of impedances of interface layers on thermoelectric devices performance was investigated by Xuan et al. and the simplified solutions at some specific conditions were presented [10]. The impact of contact resistance on thermoelectric module performance was studied by Ebling et al. based on the multi-physics finite element simulation [11]. The role of thermal boundary resistance of thermoelectric transport in heterogeneous medium was investigated by Hao et al. [12]. The performance of the TEGs has a significant reduction when the influence of contact resistance is taken into consideration as mentioned in Refs. [10–12].

From [8–12], one feature can be found that all of them are limited to the flat plate thermoelectric generators (FTEGs) where the cross-section configuration of thermoelectric leg is a flat plate. However, the heat source may be cylindrical in shape for some practical applications, such as recovery of waste heat from coal-fired boiler [13], automotive

* Corresponding authors.
E-mail addresses: zhangaibing@nbu.edu.cn (A.B. Zhang), pangdandan@hncj.edu.cn (D.D. Pang).

https://doi.org/10.1016/j.enconman.2018.04.042
Received 2 March 2018; Received in revised form 1 April 2018; Accepted 11 April 2018

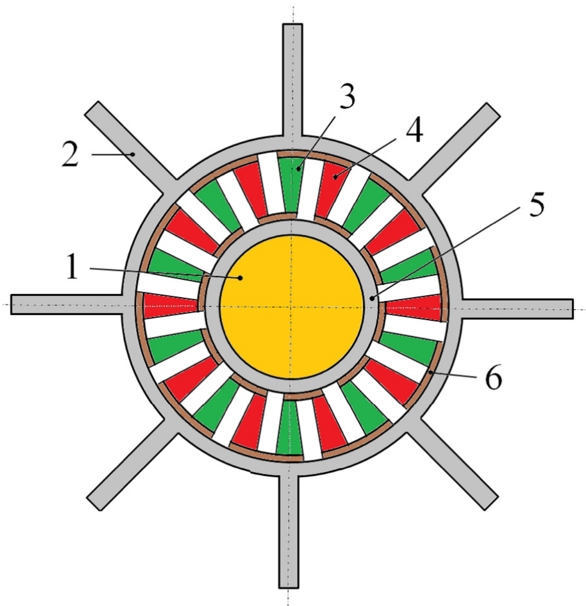

Fig. 1. Schematic diagram of an ATEG module. 1-Heat source, 2-Heat sink, 3-Positive (p) thermoelement, 4-Negative (n) thermoelement, 5-Electric insulator-thermal conductor, 6-Electrical connector.

exhaust gases [14] and radioactive isotope thermoelectric generator [15]. In these situations, low output power (per unit mass) and conversion efficiency caused by the relative geometries mismatch between the heat source (and/or heat sink) and thermoelectric couple will be presented if the FTEGs are still adopted. As a result, the annular thermoelectric generators (ATEGs) with annular shaped leg were presented by Bauknecht et al. [16], and a schematic of the structure for heat recovering of ATEG module is shown in Fig. 1. Alternating p- and n-type thermoelectric legs arranged electrically in series and thermally in parallel compose an annular thermoelectric module, and the thermoelectric legs are connected by metallic interconnector fixed at a ceramic plate. The ATEGs contact with heat source more closely and have much smaller heat transfer resistance than that of FTEGs since the shape of heat source (and/or heat sink) is cylindrical hollow. Moreover, the temperature differences of all thermoelectric couples at heat source are almost similar, the heat dissipation performance and stress concentration state of the ATEG device is much better than that of FTEG [17]. The influence of geometric feature on the dimensionless output power and conversion efficiency of an ATEG under external temperature loads was examined theoretically by Shen et al. [18]. The exergy analysis of an ATEG considering Thomson effect was carried out by Kaushik and Manikandan [19]. A general model to investigate the effect of interface layers on the performance of an ATEG was provided by Zhang et al. [20], it is found that the impedance of interface layers plays an essential role in an ATEG with the relatively short thermoelectric leg.

Although the contact resistance between heat source (and/or heat sink) and thermoelectric couple can be reduced if the ATEG device is used, however the output power (per unit mass) of ATEG is much less than that of FTEG if the thermoelectric leg is assumed to be a constant thickness [16–20]. The purpose of this paper is to present a general model to investigate the effect of the geometry configuration of thermoelectric leg and contact resistance on the performance of an ATEG. The optimized shape parameters of the leg corresponding to the maximum performance of the ATEG are obtained based on a rigorous mathematical model. The paper is organized as follows. Firstly, an ideal model of the ATEG is presented in Section 2. The optimized condition of thermoelectric leg corresponding to the maximum output power, maximum output power per unit mass and maximum conversion efficiency are given in Section 3. A general model for the ATEG by considering the contact resistance is developed in Section 4. Finally, some concluding remarks are made.

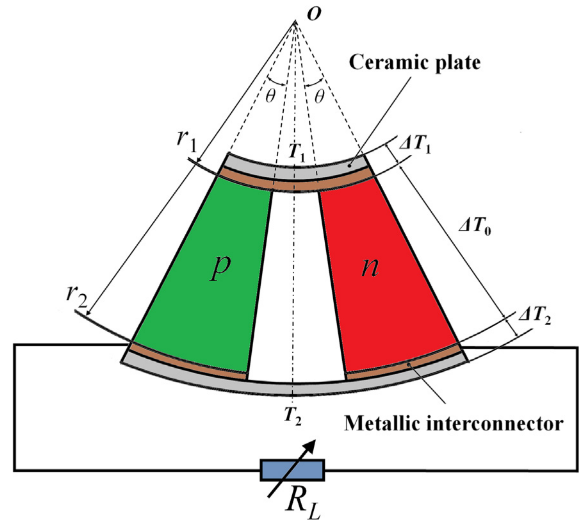

Fig. 2. A general model for an ATEG.

2. General model of an ideal ATEG

A rather idealized annular thermoelectric couple extracted from Fig. 1 is shown schematically in Fig. 2, p and n-type semiconductor thermoelements are connected by highly conducting metal strips to form an annular thermoelectric couple, sandwiched between two electrically insulating but thermally conducting ceramic plates. The electrical output power is delivered to the external loads when a temperature difference is maintained across the ATEG. The Seebeck coefficient α_p, thermal conductivity k_p and electrical conductivity σ_p of the thermoelectric leg are assumed to be constants in the currently concerned temperature range so the Thomson effect is inherently neglected. For simplicity, p and n-type legs are supposed to have the symmetric materials properties and dimensions, i.e., $\alpha_p = -\alpha_n$, $k_p = k_n$, $\sigma_p = \sigma_n$, $A_p(r) = A_n(r)$, $\delta_p(r) = \delta_n(r)$, therefore, only the p-type thermoelectric leg will be analyzed. The heat losses due to convection and radiation, and external irreversibility are not considered in this paper. In addition, the theoretical analysis is based on one dimensional steady heat transfer along the radial direction, since that the dynamic characteristics cannot be obtained. The thickness of the thermoelectric couple is assumed to be $\delta(r) = a_m r^m$, so the cross-section area $A(r)$ is varying with radius r and expressed as $A(r) = \theta a_m r^{m+1}$, where a_m and m are the shape parameter of thermoelectric leg, and θ is the angle in the direction of circumference.

The first law of thermodynamics is applied to an infinitesimal element dr of ATEG as shown in Fig. 3, and it leads to $Q_{in} - Q_{out} + Q_{gen} = 0$, where Q_{in} and Q_{out} are the Fourier heat input and output, respectively, and Q_{gen} is the Joule heat generated in the infinitesimal element. The energy conservation equation of thermoelectric material with the vary thickness $\delta(r)$ for the transport of heat and electricity can be obtained

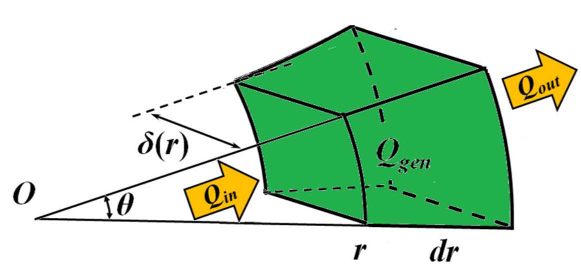

Fig. 3. Cross section of an ATEG.