Energy Conversion and Management 150 (2017) 704–713

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Assessment of the performance of annular thermoelectric couples under constant heat flux condition

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ARTICLE INFO

Keywords:
Annular thermoelectric couple
Constant heat flux condition
Theoretical analysis
Finite element method
Performance

ABSTRACT

For a round shaped heat source or heat sink, annular thermoelectric couples (ATCs) are designed to remove the contact thermal resistance induced by geometrical mismatching. In this study, the performance (power and efficiency) of ATCs subjected to a constant heat flux condition, which is often encountered in the utilization of solar energy and radiant heat, was assessed by a developed theoretical model. A finite element method was used to incorporate the temperature-dependence of thermoelectric materials and Thomson effect. The effect of annular shape parameter S_r, a parameter characterizing the geometric feature of ATCs, was particularly stressed. Also the influences of external load, heat flux, heat transfer capability at the cold junction and leg height were analyzed. The performance comparisons with the condition of constant temperature were conducted. Results show that the influence of S_r is not affected by other parameters. Contrary to a constant temperature condition, the performance enhances with S_r deviating from 1 (i.e., flat-plate thermoelectric couple), and the power increases with an increase of leg height. The external load maximizing the performance is larger than the internal electrical resistance. The larger the heat flux is, the better the performance is. As the heat transfer capability at the cold junction increases, the performance reduces, first sharply and then leveling off. Since the performance of ATCs is superior to FTCs and the undesired contact thermal resistance can be eliminated by the use of ATCs, the potential of ATCs is demonstrated.

1. Introduction

Both environmental pollution and energy crisis urge the development of green energy conversion technologies. Thermoelectric generator, which shares the characteristics of high reliability, long lifetime, noiselessness, no-moving parts and non-selection to heat source [1–3], has attracted ever-increasing attention in recent years [4]. However, because of the low efficiency [5], the current applications are mainly limited to two fields. Offering reliable power is one of the two. It includes the supply of power to wireless sensor in power grids [6] and unmanned spacecrafts for deep space exploration [7]. The other one is to recover or utilize the low cost and cost-free energy, such as geothermal energy [8], solar energy [9] and waste heat from stoves [10,11] and vehicle exhaust gases [12].

In general, a thermoelectric generator consists of a series of thermoelectric couples (TCs) connected together electrically in series and thermally in parallel. Each TC is composed of an n-type leg and a p-type leg. The performance of thermoelectric generator depends on three factors, which are the figure of merit of material, the geometric configuration of leg and the temperature difference of two junctions. In order to extend the application fields and promote the commercialization of thermoelectric technologies, extensive studies in regard to these three factors have been carried out. Zhao et al. [13] reported an ultrahigh dimensionless figure of merit zT of 2.6 for p-type SnSe single crystals. To match this, n-type SnSe single crystals with zT of 2.2 were fabricated by Duong et al. [14]. Sahin and Yilbas [15] theoretically studied the influence of leg geometry on the efficiency and power of TCs. Compared with the leg shaped in rectangular, the efficiency enhanced significantly with the leg shaped in trapezoid. By using the nominal power density analysis, performance comparisons of TCs with three different leg geometries, i.e., leg in linear, quadratic and exponential cross-sectional functions, were conducted by Shi et al. [16]. Among them, the TC with leg in linear variation in cross section had the highest performance. On the basis of numerical study, Reddy et al. [17] analyzed the thermoelectric-hydraulic performance of an integrated thermoelectric generator. Results showed that the performance can be

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http://dx.doi.org/10.1016/j.enconman.2017.08.058
Received 30 May 2017; Received in revised form 3 August 2017; Accepted 20 August 2017

Nomenclature

A	cross-section area, m^2
H	height, m
H_0	reference height, m
i, j	positive integer
I	current, A
k	thermal conductivity, W/(mK)
K	thermal conductance, W/K
K_C	heat transfer capability at the cold junction, W/K
$K_{C,0}$	reference heat transfer capability, W/K
L	width, m
m, n	segment
N	number of thermoelectric couples
P	power, W
P_{min}	minimum power, W
Q_c	heat dissipated at the cold junction, W
Q_{in}	input heat flux, W
$Q_{in,0}$	reference input heat flux, W
r	radial direction; position, m
R_t	internal electrical resistance, Ω
R_L	external load, Ω
S_r	annular shape parameter
T	temperature, K
T_a	ambient temperature, K
T_m	average temperature, K
ΔT	temperature difference, K
V	volume, m^3
V_0	reference volume, m^3
z	figure of merit, K^{-1}
zT	dimensionless figure of merit

Greek symbols

α	Seebeck coefficient, V/K
δ	thickness, m
η	efficiency
ρ	electrical resistivity, Ω m
$\Delta\varphi$	center angle

Subscripts

c	cold junction
h	hot junction
n	n-type leg
p	p-type leg

Abbreviations

ATC	annular thermoelectric couple
FTC	flat-plate thermoelectric couple
TC	thermoelectric couple

notably affected by leg height.

The heat transfer capabilities between the thermoelectric generator and heat source or heat sink are crucial to the temperature difference. The larger the heat transfer capabilities have, the higher the temperature difference and the performance enjoy. To enhance the heat transfer capabilities, some approaches were proposed and identified. With experiments, the effects of flow channel inserts, i.e., panel and spiral, on the performance of thermoelectric generator were studied by Lesage et al. [18]. Compared with the spiral insert, the power generation was considerably increased by the use of panel insert. After that, Amaral et al. [19] investigated the influence of panel insert density. Experiments showed that the optimal panel insert densities maximizing the net power under different flow rates were different. Three exhaust gases heat exchangers featured by fishbone-shaped, accordion-shaped and scatter-shaped internal structures were simulated by Su et al. [20]. The surface temperature of the heat exchanger with accordion-shaped structure was the highest. Kim et al. [21] carried out simulations to optimize the internal plate fin structure of heat exchanger. The hot side temperature of thermoelectric generator increased with increasing fin thickness or number of fins. It should be noted that for inserting inserts or fins in heat exchanger, not only the heat transfer capability but also the pressure drop and the dissipated pump power increase, so the net enhancement is very limited or even negative [18,19]. Thus, another measure, which uses passive heat transfer components with high thermal performance such as heat pipe and thermosyphon, has been developed. Date et al. [22] theoretically and experimentally studied a heat pipe based solar thermoelectric generator. A thermoelectric generator with thermosyphon heat exchanger was tested and modeled by Araiz et al. [23]. Compared with the finned heat exchanger under forced convection, the net power was increased by 36% by the use of thermosyphon heat exchanger.

A literature review shows that all studies above are limited to the flat-plate thermoelectric couple (FTC), which is characterized by the cross-section of leg shaped in flat-plate. FTC is a good choice for flat-plate heat sources or heat sinks. While for round shaped heat sources or heat sinks [24–26], FTC may be not suitable, due to a considerable contact thermal resistance caused by geometrical mismatching [27,28]. Consequently, a thermoelectric couple with annular shape leg, named annular thermoelectric couple (ATC) was put forward recently. A thermoelectric generator with two ATCs was fabricated and its performance was tested and computed by Min and Rowe [27]. Similar to the conventional generator with FTCs, the power production increased with increasing temperature difference. Bauknecht et al. [29] numerically analyzed the influence of non- uniform temperature distribution on the performance of ATCs used for waste heat recovery of vehicles. The efficiency decreased with temperature distribution deviating from uniform. The effect of annular shape parameter characterizing the geometric feature of ATC, was theoretically analyzed by Shen et al. [30]. The power and maximum efficiency of ATC were respectively lower than and equal to those of FTC. After that, an exergy analysis on a ATC was performed by Kaushik and Manikandan [31]. Compared with the FTC, the exergy efficiency of ATC was lower. An investigation on an ATCs based solar heat pipe thermoelectric generator system was carried out by Manikandan and Kaushik [32]. Both overall exergy efficiency and power were slightly higher than those of FTCs based system. Also, the ATC used as a thermoelectric cooler was researched in Ref. [33]. From Refs. [27,29–33], it can be concluded that the study on ATC is very limited up to now. Besides, in the theoretical analyses [27,30–33], the constant values [27,29,30] or the values based upon the average temperature of junctions [31,32] were used for the properties of thermoelectric materials, i.e., the temperature-dependence of materials was not taken into account properly. As a result, the accuracy of results cannot be ensured [34]. Moreover, most of the studies [27,29–31,33] are subjected to a constant temperature condition. Due to the fact that a lot of energy supply through a large heat source is required under this condition, it is unrealistic and instead a constant heat flux condition may be more realistic [35] for practical applications such as the utilization of solar energy [9,24,26,35–39] and recovery of radiant heat from steelmaking process [40] and silicon production [41,42]. Under a constant heat flux condition, the hot junction temperature is not fixed but depends on the incoming heat flux and the heat transfer capability at the cold junction [35]. The FTC and FTCs based thermoelectric generator under a constant heat flux condition were studied by Refs. [9,24,26,35–43].