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Theoretical analysis on the performance of annular thermoelectric couple

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ABSTRACT

For round shaped heat source or heat sink, the annular thermoelectric couple (ATEC) with annular shaped legs instead of flat-plate thermoelectric couple (FTEC) is proposed to solve the performance deterioration caused by geometries mismatching. Based on one-dimensional steady model, the fundamental formulas of ATEC are derived. The impact of geometric feature of ATEC manifested by the annular shaped parameter s_r, on the dimensionless output power and efficiency of ATEC under different temperature ratios, external loads and dimensionless figure of merits is examined theoretically. Also, to enhance the practicability of ATEC, some suggestions or notes are provided. Results show that the forms of fundamental formulas about ATEC are the same as those about FTEC. Compared to temperature ratio and dimensionless figure of merit, the influence of s_r is affected by external load seriously. The extremums of dimensionless output power and efficiency are presented on condition that $s_r = 1$. As the closer s_r is to 1, the larger the dimensionless output power is. In view of this behavior, a new structure including an additive material with high thermal conductivity is designed for recovering cost-free energy resources with ATEC.

1. Introduction

As a result of energy crisis and environmental pollution followed by immoderately burning fossil fuels in recent several decades, many efforts have been poured into the researches of renewable clean energy resources. Thermoelectric power generation, because of its simplicity, less maintenance cost, high reliability and environmental friendliness, has become a promising clean energy conversion technology. However, due to the relatively low thermal-to-electric efficiency compared to conventional power generation technologies [1], the commercialization of this technology is limited, mainly in the fields of low cost or cost-free energy resources, such as solar energy [2–4] and waste heat from automotive exhaust gases [5,6].

The performance of thermoelectric generator (TEG) composed of a series of thermoelectric couples is directly related to the dimensionless figure of merit (*ZT*), geometric arrangement of thermocouple, external load and temperatures of cold and hot junctions. To increase the competitiveness of thermoelectric power generation technology, extensive investigations have been conducted.

Considerable improvement about *ZT* was obtained in recent decades. Zhao et al. [7] reported a *ZT* of 2.9 at 923 K in SnSe single crystals, which was the highest up to present. By introducing shape parameter, Sahin and Yilbas [8] and Ali et al. [9] investigated the effect of leg geometry on the performance of thermoelectric couple. Ref. [8] showed that the efficiency of thermoelectric couple increased notably when the leg geometry became a trapezium shape along the leg height. Optimal external load for peak power of a TEG in solar application was carried out by Lesage et al. [10] using two experimental apparatuses. They indicated that the load matching condition cannot yield peak power for any of the thermal conditions tested. Also, a simplified normalized power relation was put forward.

The temperatures of cold and hot junctions were determined by heat transfer capabilities between TEG and heat source or heat sink. Some appropriate approaches for increasing heat transfer capabilities were proposed and investigated. In detail, Crane and Jackson [11] created a numerical model and studied an integrated thermoelectric cross flow heat exchanger. Based on theoretical and experimental studies, some suggestions for performance improvement of TEG were proposed by Gou et al. [12], such as expanding heat sink surface area in a proper range and enhancing cold-side heat transfer capacity in a proper range. The performance of TEG at various operating conditions was studied experimentally by Chen et al. [13]. Results showed that the effects of flow pattern

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Nomenclature

A	cross-section area of leg, m^2
I	electrical current, A
k	thermal conductance of leg, W/(m K)
K	overall thermal conductance of ATEC, W/(m K)
P	output power of ATEC, W
Q	heat flow rate, W
Q_{in}	Fourier heat input, W
Q_{out}	Fourier heat output, W
Q_J	Joule heat, W
r	radial direction
R	total electrical resistance of ATEC, Ω
R_L	external load, Ω
s_r	annular shaped parameter
T	temperature, K
T_m	average temperature, K
ZT_m	the dimensionless figure of merit

Greek symbols

α	Seebeck coefficient, V/K
λ	thermal conductivity of leg, W/(m K)
σ	electrical conductivity of leg, Ω^{-1} m^{-1}
$\Delta\varphi$	angle in the direction of circumference, rad
δ	thickness of leg, m
θ	dimensionless temperature ratio
η	efficiency of ATEC

Subscripts

n	n-type leg
p	p-type leg
0	reference position
1	hot junction
2	cold junction

of heat sink and water flow rate were not significant, but the heat source temperature played an important role. Love et al. [14] investigated the influences of heat exchanger material and fouling on TEG exhaust heat recovery. They pointed out that the performance of thermoelectric device with stainless steel heat exchanger was lower than that with aluminum heat exchanger due to the difference of thermal conductivity, and heat exchanger fouling can degrade the performance of studied devices. Using exhaust gas of vehicles as heat source, a mathematical model for the performance of TEG devices was developed by Wang et al. [15]. The findings revealed that the benefit caused by changing the convection heat transfer coefficient of high-temperature side was more pronounced than that of low-temperature side. The power output characteristics of TEG with plate-fin heat absorber were investigated by Jang et al. [16] using three-dimensional numerical method. Results indicated that the optimal fin height and flue gas velocity existed for maximizing net power density. In the experiment conducted by Lesage et al. [17], the effects of two flow channel inserts (panel and spiral inserts) strengthening the heat transfer coefficient on power generation of liquid-to-liquid TEG were considered. It was shown that the panel inserts enhanced power up to 110%, while the spiral inserts produced negligible power enhancement. Using the same experimental apparatus presented in Ref. [17], the net power output of TEG under various panel densities of flow impeding geometric inserts was explored by Amaral et al. [18]. Optimal insert panel density maximizing the net power was identified with respect to flow rate. A micro-TEG was proposed and its performance was researched by Wojtas et al. [19]. This device had the advantages of high heat transfer coefficient and small pumping power in a compact volume. Results suggested that the optimization for thermoelectric material should focus more on the power factor than on ZT itself when systems had good thermal coupling. Besides, Wang et al. [20] designed the geometry of heat sink such as fin spacing and length with two-stage optimization. Jang and Tsai [21] optimized TEG modules pacing and its spreader thickness using a simplified conjugate-gradient method. Tzeng et al. [22] discussed the configurations and dimensions of heat absorber and heat sink by applying one-dimensional steady model. Also, heat pipe [23,24] and thermosyphon [25] heat sink were employed in solar hybrid systems with TEGs to enhance heat transfer capability.

From Refs. [11–25], two features have been found. On one hand, all of them were limited to flat-plate thermoelectric couple (FTEC), where the cross-section shape of legs was flat-plate. On the other hand, almost all of these studies were concentrated on methods to increase heat transfer coefficient, which included altering flow patterns [13] and heat exchanger materials [14], adding flow channel inserts [17,18], applying micro fluidic heat transfer system [19], heat pipe [23,24] and thermosyphon [25]. However, in some practical applications, such as converting heat from automotive exhaust gases [5,26] and from coal-fired boiler [27], utilizing solar energy with heat pipe [23,24] or thermosyphon [25], the heat source or heat sink is cylindrical in shape. In these situations, if FTEC was still adopted, poor heat transfer capability caused by the relative geometries of heat source or heat sink and thermoelectric couple would be presented [10] in spite of taking above methods to increase heat transfer coefficient. Consequently, the performance of thermoelectric couple would be degraded and the commercialization of thermoelectric power generation technology would be further postponed. In this regard, annular thermoelectric couple (ATEC) with annular shaped leg is proposed, ascribing to the fact that ATEC can contact with heat source or heat sink closely showing much smaller heat transfer resistance than that of FTEC. Currently, the annular shaped thermoelectric module has already been fabricated [28]. Yet, to the best knowledge of authors, the study related to ATEC has received very little attention, and the impact of annular shaped parameter characterizing the feature of ATEC on the performance of thermoelectric couple is blank. What's more, considering the fact that non-constant cross-section along thermocouple leg and annular shape are presented in ATEC, some new behaviors may occur, such as the allocation of generated Joule heat on both junctions of ATEC. Thus the previous formulas preparing for FTEC may be inapplicable to ATEC.

In the present study, taking ATEC as object, the fundamental formulas of ATEC including temperature distribution along the legs, heat absorbed at hot junction and dissipated at cold junction, output power and efficiency, are derived based on one-dimensional steady model. Then the effect of annular shaped parameter on the performance of ATEC under different operating temperature ratios, external loads and ZT is theoretically analyzed. In the end, some suggestions or notes for practical applications of ATEC are provided.

2. Theoretical model

A typical ATEC is presented in Fig. 1, which consists of a p- and n-type thermoelectric legs sandwiched between heat source and heat sink. The first part of this study is to derive the fundamental formulas of ATEC. Fig. 2 shows the physical model of one leg. In