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Numerical study on the thermal and electrical performance of an annular thermoelectric generator under pulsed heat power with different types of input functions

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ABSTRACT

The study of annular thermoelectric generators (ATEG) has attracted more attention in recent years due to their ability to cover round shaped surfaces. Moreover, transient and pulsed inputs have been introduced as some of the effective methods to enhance the performance of thermoelectric devices. Hence, in the present study, a three-dimensional transient simulation of ATEG including the influence of Thomson effect is carried out based on finite element method. The effect of pulsed heat inputs on the performance of ATEG is studied considering rectangular, triangular, sinusoidal and two types of the sawtooth input functions for modeling the transient heat load. Electric current, voltage, output power and conversion efficiency of ATEG under pulsed and steady-state heating are compared. The effects of two critical parameters, the ratio of maximum heat flux to minimum heat flux (b/a) and duty cycle (t_0/τ) values on the performance of ATEG are studied. Results indicate that transient pulsed heating enhances the efficiency of ATEG for all types of heat input functions. In addition, it is found that rectangular input function leads to better results compared to other functions. Also, it is shown that for a constant amount of duty cycle, the increment of (b/a) increases the performance of ATEG unit. For duty cycle value of 0.1 and ($b/a = 48$) a maximum efficiency enhancement of 249.36% is achieved when the rectangular input function is employed. It is found that in the range of the studied values of (b/a), the duty cycle of 0.4 leads to better results. A comparison of results with and without Thomson effect proves that the Thomson effect decreases the performance of ATEG. Additionally, it is observed that for sawtooth input functions, the implementation of heat load gradient plays an important role determining the performance.

1. Introduction

Thermoelectric is defined as the science and technology associated with thermoelectric generation and refrigeration. A thermocouple uses the electrical potential (electromotive force) generated between two dissimilar wires to measure temperature. Basically, thermoelectric consists of two devices: a thermoelectric generator (TEG) and a thermoelectric cooler (TEC). These devices have no moving parts and require no maintenance. Thermoelectric generators have a great potential for waste heat recovery from power plants and automotive vehicles. These devices also provide reliable power in remote areas such as in space and at mountaintop telecommunication sites [1,2].

Thermoelectric modules have been studied for many years since the discovery of Seebeck effect. Many researchers reviewed the recent developments and potentials of thermoelectric devices for renewable and sustainable energy applications [3–9]. Due to lower efficiency of these devices, their application has not become widespread yet. The increment of the efficiency of thermoelectric devices can be achieved by developing more efficient material [10,11] and performing geometrical optimizations. Improving the performance of thermoelectric devices with the method of producing new materials is obtained by increasing the conversion efficiency in the form of the thermoelectric figure of merit which is defined by $ZT = S^2T\sigma/k$, where S,σ,k and T are the Seebeck coefficient, electrical conductivity, thermal conductivity and absolute temperature, respectively. An ideal thermoelectric material must exhibit, high electrical conductivity, high Seebeck coefficient, and low thermal conductivity. The high Seebeck coefficient ensures a large potential/thermovoltage, the high electrical conductivity is needed to minimize the Joule heating effect, and the low thermal conductivity is needed to create a large temperature gradient [12].

On the other hand, geometrical optimization of thermoelectric devices has focused on two main design aspects of the modules, developing the more efficient arrangement of the legs and changing pin geometry to get higher values of conversion efficiency. A lot of studies

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Nomenclature

A	area (m^2)
a, b	heat flux (Wm^{-2})
C_p	heat capacity at constant pressure (Jkg^{-1} K^{-1})
E	electric field (Vm^{-1})
J	electric current density (Am^{-2})
k	thermal conductivity (Wm^{-2} K^{-1})
P	power (W)
Q	heat power (W)
q''	heat flux (Wm^{-2})
R	electrical resistance (Ω)
r	radius (m)
S	Seebeck coefficient (VK^{-1})
T	temperature (K)
t	time (s)
t^0	heating time (s)
t_W	thickness (m)
V	voltage (V)

Abbreviations

ATEC	annular thermoelectric couple
ATEG	annular thermoelectric generator
PH	pulsed heating
SSH	steady-state heating
SATEG	solar annular thermoelectric generator
TEC	thermoelectric couple
TEG	thermoelectric generator

Greek letters

β,γ	angle (degree)
η	conversion efficiency
Δ	difference
ρ	density kgm^{-3}
σ	electrical conductivity (Sm)
τ	time period (s)
φ	angle (degree)

subscript

c	cold side
h	hot side
in	input
L	load
n	n-type
oc	open-circuit
out	output
p	p-type
PH	pulsed heating
ss	steady-state

have been carried out to investigate the influence of pin geometry on the performance of thermoelectric generators (TEG) [13–15]. Linear, multi-stage, helical and corrugated configuration of thermoelectric legs are some of the different arrangements studied with the aim of developing more efficient thermoelectric devices [16–20]. However, most of the designs presented in various structures are aimed at covering the flat surfaces. In some practical applications, such as converting heat from automotive exhaust gases and from coal-fired boiler, utilizing solar energy with heat pipe or thermosyphon, the heat source or heat sink is cylindrical in shape, and if the flat thermoelectric structure was still adopted, poor heat transfer capability caused by the relative geometries of heat source or heat sink and thermoelectric couple would be presented [21]. The Annular shaped legs are some of the promising designs that have been proposed to cover the heat sources or heat sinks with round shaped structure. Also, annular thermoelectric couples have an increasing cross-sectional area along the radial direction which can result in the higher available total heat transfer area compared to flat thermoelectric couples. Gao Shen et al. [21] have theoretically studied the one dimensional model of the annular thermoelectric couple (ATEC). The fundamental formulas of ATEC have been derived based on one-dimensional steady-state model and the influence of different geometrical features on output power and efficiency of ATEC under different operating conditions has been investigated. Results show that the general forms of these fundamental formulas are the same for ATEC and classic flat thermoelectric couples. They have also studied the effect of the annular shaped parameter which is the ratio of the outer radius to the inner radius of the annular shaped leg ($S_r = r_2/r_1$) on the performance of ATEG unit and proved that $S_r = 1$ (flat thermoelectric couple) leads to highest power output. Kaushik and Manikandan [22] have investigated the influence of the Thomson effect on energy and exergy efficacy of annular thermoelectric generator (ATEG). New expressions for optimum current at the maximum power output and maximum energy and exergy efficiency of the ATEG are derived. The energy and exergy efficiencies of solar annular thermoelectric generator (SATEG) considering the Thomson effect have been studied by Manikandan and Kaushik [23]. They have reported 0.52% and 0.4% overall gain in power output and exergy efficiency of the device respectively when SATEG is used instead of the flat solar thermoelectric generator. The performance (power and efficiency) of ATEC subjected to a constant heat flux condition, which is often encountered in the utilization of solar energy and radiant heat, was assessed with a developed theoretical model by Zu-Gao Shen et al. [24]. They used the finite element method to further incorporate the temperature-dependence of thermoelectric material and Thomson effect. The effect of several effective parameters including external load, heat flux and shape parameter has been studied and compared with the constant temperature condition.

In addition to the use of geometrical optimization and development of more efficient material, transient and pulsed inputs have been introduced as some of the effective methods to enhance the performance of thermoelectric modules in recent years [25–29]. Chakraborty and Choon Ng [30] have presented a thermodynamic formulation for the operation of pulsed thermoelectric cooler using the Gibbs and simple energy balance method. Ahamat and Tierney [31] have investigated the effect of transient temperature variation of the thermoelectric surface on the heat transfer rate into the module. Sinusoidal, triangular and constant temperature variations with respect to time have been tested. Montecucco et al. [32] have studied the transient behavior of thermoelectric devices. A one-dimensional transient solution to heat conduction equation with internal heat generation that describes the transfer and generation of heat throughout a thermoelectric device has been presented. Ming Ma et al. [33] numerically have investigated the effect of pulsed current on thermal performance of a thermoelectric cooler. Results show that applying a current pulse before the temperature condition of the cold side being recovered to initial values would result in a temperature increase in the next current pulse. Chen and Lee [34] have performed a numerical simulation to investigate the transient response of thermoelectric generator to pulsed heat power. The amounts of increase in conversion efficiency, thermal and electrical performance of TEG under periodic heating have been studied. They have reported that a rectangular pulsed heat leads to better results than alternate temperature gradient in terms of conversion efficiency under the same input power condition. It is found that the ratio of maximum input heat flux to the minimum input heat flux plays an important role in the enhancement of performance of TEG in periodic heating. The