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Thermodynamic analysis of thermoelectric generator including influence of Thomson effect and leg geometry configuration

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ABSTRACT

To improve the power output and efficiency of the thermoelectric generator system, the variation in the thermoelectric leg configuration is another option. In this paper, the thermodynamic analysis of exoreversible thermoelectric generator including influence of Thomson effect as well as influence of leg geometry on the power output and efficiency of the device has been carried out. The modified expressions for dimensionless figure of merit, power output, irreversibilities, energy and exergy efficiency considering Thomson effect have been derived analytically. The effects of various parameters such as dimensionless temperature ratio (θ), shape parameter (R_A), Thomson effect and load resistance ratio (R_L/R_0) on the power output, energy and exergy efficiency have been studied. The operating range for shape parameter has been found which improves the power output, energy and exergy efficiency of the device, however, the optimum operating point corresponding to maximum power output is different from that of the maximum energy and exergy efficiency. The results of this study shows that when the shape parameter is increased from 1 (flat plate TEG) to 2 (trapezoidal TEG), then the energy and exergy efficiency improve by 2.32% and 2.31% respectively with a 1.3% decrease in power output at R_L/R_0 = 10 and θ = 0.5. This study will help in designing of the improved thermoelectric generator systems for different leg geometries.

1. Introduction

The increasing imbalance between demand and supply of energy and continuous environmental degradation leads the researchers to investigate environment friendly, clean renewable energy resources. Thermoelectric (TE) devices are one of the most promising and cost effective renewable energy resource. Thermoelectric devices, being solid state direct energy conversion device convert thermal energy into electrical energy directly or vice-versa using the reversible Seebeck and Peltier phenomena [1–5]. Thermoelectric devices work as a heat engine operating between two heat reservoirs. Thermoelectric devices offer the features of noiseless operation, light weight, absence of moving parts which results in increased system life, increased reliability and very less maintenance [6–8]. The absence of working fluid removes the problem of environmentally dangerous greenhouse emission. These features motivate the researchers to work more in the direction of thermoelectric devices. However, the thermoelectric devices have lower efficiency due to the irreversible heat conduction and Joule heating caused by thermoelectric properties of thermoelectric material and due to the external irreversible heat transfer from heat source to hot side and from cold side to heat sink. This relatively low heat to electricity conversion efficiency limits the wide applications of thermoelectric devices as a power generator. Therefore, thermoelectric devices are used efficiently for low power applications compared to conventional thermodynamic devices for power generation [9].

The performance of thermoelectric devices can be improved by two pathways [10]. One is by improving the intrinsic efficiency of thermoelectric material and another is by improving the ways of use of existing thermoelectric systems. To improve the efficiency of thermoelectric devices, the research efforts in materials are underway. By changing the leg geometry of thermoelectric element comes under the way of improving the performance of existing thermoelectric devices. The flat plate single and multistage thermoelectric generators have been investigated thermodynamically by many researchers [11–15]. Sahin and Yilbas [16] analysed the performance of thermoelectric power generator and influence of thermoelectric leg geometry on the device performance theoretically. They concluded that the shape parameter of the device has favourable effect on efficiency and adverse effect on the power output. Ali et al. [17] performed the thermodynamic analysis of thermoelectric power generator with influence of pin leg geometry on the device performance and found out that the system efficiency is

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Nomenclature

A	area (m^2)
Ex	exergy (W)
E_{Qh}	exergy associated to heat input (W)
I	electrical current (A)
Irr	irreversibility (W)
k	thermal conductivity (W/m K)
K	thermal conductance (W/K)
L	length of TE element leg (m)
P	electrical power (W)
Q	heat (W)
R	electrical resistance (Ω)
R_A	geometric/shape parameter
S	entropy (W/K)
T	temperature (K)
Z	figure of merit (1/K)
Greek letters	
θ	dimensionless temperature
α	Seebeck coefficient (V/K)
η	energy efficiency
ρ	electrical resistivity (Ω-m)
σ	electrical conductivity (S/m)
Δ	difference
ψ	exergy efficiency
τ	Thomson coefficient (V/K)
Subscripts	
a	environment
c	cold side of TEG
d	destroyed
dr	infinitesimal
eff	effective
gen	generation
h	hot side of TEG
in	input
Irr	irreversibilities
k	thermal conductivity
$loss$	loss
L	load
m	mean
n	n type material
o	reference
out	output
p	p type material
$storage$	storage
t	total
σ	electrical conductivity

improved by increasing the dimensionless geometric parameter. Shen et al. [18] proposed a different configuration called annular thermoelectric generator in which annular shaped legs have been used and found out that the efficiency of annular thermoelectric generator is lower than that of flat plate thermoelectric generator. Al-Merbati et al. [19] performed the thermodynamic and stress analysis of thermoelectric generator with influence of thermoelectric leg geometry on thermal stress, power output and thermal efficiency. The performance of thermoelectric devices depends on the operating temperature, figure of merit of thermoelectric element material and geometric configuration. The efficiency of thermoelectric devices is lower due to inherent irreversibilities in the thermoelectric material which results in figure of merit of order of 1.

The geometric configuration of thermoelectric legs affects the device performance; therefore it is essential to investigate the influence of leg geometry on the power output and thermal efficiency of the device. Lavric [20] carried out the one dimensional thermal analysis of thermoelectric devices with effect of geometry for practical applications and concluded that by reducing the length of the thermoelectric element leg reduces the electrical resistance while larger legs result in high temperature difference between the two ends of the legs. Vatcharasathien et al. [21] carried out the design and thermal analysis of solar thermoelectric generator by considering truncated parabolic collectors with flat receiver, conventional flat plate collectors. Gou et al. [22] developed a thermodynamic model and performed experimental study of thermoelectric devices for low temperature waste heat applications and suggested that by enhancing cold side heat transfer coefficient by increasing heat sink surface area improve the performance of thermoelectric devices. Amatya and Ram [23] presented the thermodynamic analysis of solar thermoelectric generator to predict the thermal to electricity conversion efficiency for micro power applications. Suzuki and Tanaka [24] carried out the simulation study for the performance analysis of multi panel thermoelectric generators and concluded that the TE device area can be reduced significantly by proper arrangement of thermoelectric panels. Chen et al. [25] studied the performance of thermoelectric generator at different operating conditions experimentally and concluded that the heat source temperature affects the performance of the device significantly. The influence of Thomson effect on the power output and energy efficiency of flat plate thermoelectric generator has been studied by Chen et al. [26]. The influence of Thomson effect on the thermoelectric cooler has been studied by different authors time by time [27–29]. The theory of finite time thermodynamics or entropy generation minimization is a powerful tool for the performance analysis of thermodynamic systems. The performance of thermoelectric devices has also been analysed using finite time thermodynamics and non-equilibrium thermodynamics. The feasibility and performance analysis of a single and two sage thermoelectric refrigerator or heat pump driven by a single or two stage thermoelectric generator have been carried out by Chen et al. [30,31] and Meng et al. [32–35]. Wang et al. [36] have carried out the performance analysis of thermoelectric systems based on entropy generation minimization method analytically. Kaushik and Manikandan [37] carried out the energy and exergy analysis of annular thermoelectric generator including Thomson effect and concluded the Thomson effect lowers the performance of thermoelectric generator. Kaushik and Manikandan [38,39] carried out the influence of Thomson effect on the performance optimization of two stage thermoelectric generator and two stage thermoelectric cooler.

Based on the literature survey, it is clear that the thermodynamic analysis of thermoelectric device including Thomson effect has been presented extensively. There are some studies in the literature which considers the effect of leg geometry on the performance of the device [16,17,19,40]. However, these studies do not consider the influence of Thomson effects on the power output and efficiency of the pin geometry (trapezoidal) TE device. In the present study, the thermodynamic analysis of thermoelectric generator including influence of Thomson effect as well as influence of leg geometry on the performance of the device has been carried out theoretically. It is assumed that half of the Thomson heat, generated within the thermoelectric generator flows towards hot