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The influence of Thomson effect in the energy and exergy efficiency of an annular thermoelectric generator

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ABSTRACT

The exoreversible thermodynamic model of an annular thermoelectric generator (ATEG) considering Thomson effect in conjunction with Peltier, Joule and Fourier heat conduction has been investigated using exergy analysis. New expressions for optimum current at the maximum power output and maximum energy, exergy efficiency conditions, and dimensionless irreversibilities in the ATEG are derived. The modified expression for figure of merit of a thermoelectric generator considering the Thomson effect has also been obtained. The results show that the power output, energy and exergy efficiency of the ATEG is lower than the flat plate thermoelectric generator. The effects of annular shape parameter ($S_r = r_2/r_1$), load resistance (R_L), dimensionless temperature ratio ($\theta = T_h/T_c$) and the thermal and electrical contact resistances in power output, energy/exergy efficiency of the ATEG have been studied. It has also been proved that because of the influence of Thomson effect, the power output and energy/exergy efficiency of the ATEG is reduced. This study will help in the designing of the actual annular thermoelectric generation systems.

1. Introduction

In recent years, the need for electrical energy is increasing by multi fold. With the limited availability of conventional energy resources, smart method of utilization of available energy is becoming significant. Thermoelectric power generation is a solid state direct energy conversion technique for converting heat into electricity [1–3]. It operates on the principle of Seebeck effect. Thermoelectric generator works as a heat engine operating between the two heat reservoirs and its actual efficiency is lower than the ideal Carnot efficiency because of the irreversibilities induced by the electrical, thermal and the thermoelectric properties of the thermoelectric materials.

Thermoelectric devices have advantages of being solid state device with no moving parts and rarely require maintenance, provides noiseless operation, it offers light weight and compactness and hence occupy small space [4]. Thermoelectric devices have better efficiency at lower power levels compared with conventional thermodynamic devices for power generation and space conditioning. Therefore, these devices are best suited for low power applications [5].

Single and multistage flat-plate thermoelectric generators (FTEGs) have been analysed thermodynamically [6–11]. Chen et al. [12] studied the impact of Thomson effect in the energy efficiency and power output of the flat plate thermoelectric generator system and found that the Thomson effect reduces the power output and energy efficiency considerably. Huang et al. [13,14] and Chen et al. [15] studied the influence of Thomson effect in the thermoelectric cooler system. Rabri et al. [16] and Xiao et al. [17] have studied the effect of convection heat transfer in the flat plate thermoelectric generator and found that the convection heat transfer from the thermoelectric couple to the surrounding environment reduces the energy efficiency and power output considerably. Manikandan and Kaushik [18] studied the thermoelectric generator operated thermoelectric cooler combined system for low cooling power applications with maximum power point tracking technique. Solar operated thermoelectric generator systems and waste heat driven thermoelectric power systems have been analysed [19–22]. All these applications require higher heat transfer coefficient at the cold side to enhance the performance of the thermoelectric generator system. Therefore, it is desirable to have a thermoelectric geometry with higher heat transfer area at its cold side.

Sahin and Yilbas [23] and Ali et al. [24] studied the thermoelectric couple with trapezoidal geometry and found that the energy conversion efficiency is higher than the flat plate geometry of thermoelectric couple. Shen et al. [25] studied the annular thermoelectric generator without considering the Thomson effect and found that the energy efficiency of ATEG is lower when compared with FTEG. Bauknecht et al. [26] studied the performance inhomogeneity in a ring shaped thermoelectric couples because of various flow

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Nomenclature

r	radius (m)
A	area (m^2)
Ex	exergy (W)
I	current (A)
Irr	irreversibility (W)
K	thermal conductance (W/K)
P	electrical power (W)
Q	heat (W)
R	electrical resistance (Ω)
S	entropy (W/K)
T	temperature (K)
Z	figure of merit (1/K)
Greek letters	
θ	dimensionless temperature (theta)
α	seebeck coefficient (V/K)
η	energy efficiency
k	thermal conductivity (W/m K)
ρ	electrical resistivity (Ω m)
σ	electrical conductivity (S/m)
Δ	difference
Ψ	exergy efficiency
φ	angle
τ	Thomson coefficient (V/K)
δ	thickness (m)
Subscripts	
1	inner
2	outer
a	environment
c	cold side of TEG
d	destroyed
dr	infinitesimal
gen	generation
h	hot side of TEG
in	input
$loss$	loss
m	mean
n	n type material
o	reference
out	output
p	p type material
$storage$	storage
t	total
Qh	heating power

patterns of hot flue gas in an ATEG using 3D multiphysics simulation and found that a suitable flow pattern of hot flue gas should be employed for homogenization of the surface temperature to get better performance.

Cvahtet and Strnad [27] thermodynamically analysed the ideal thermoelectric heat engine and heat pump and compared it with the actual systems. Nuwayhid et al. [28] and Wang et al. [29] have analysed the thermoelectric system based on entropy generation minimization method. Sharma et al. [30] have carried out simple exergy analysis of single and multistage exoreversible thermoelectric cooling system. Tipsaenporm et al. [31] have proposed thermodynamic analysis in thermoelectric cooler and found out second law efficiency is less than the first law (energy) efficiency. Kaushik et al. [32] have performed detailed exergy analysis of a thermoelectric heat pump system and found that the exergy analysis is useful to identify actual irreversibilities in the thermoelectric systems because, exergy analysis provides true measure of efficiency since it takes into considerations of first and second law of thermodynamics. With this technique the actual exergy destruction in the system can be located so that the avoidable exergy losses can be reduced by taking corrective actions [33–36].

Based on the literature survey, it is found that the exergy analysis in annular thermoelectric generator systems has not been carried out. The effect of thermal and electrical contact resistance and the Thomson effect in energy/exergy efficiency of ATEG are also not been studied. Therefore, it is desirable to carryout exergy analysis in the annular thermoelectric generator system. In this study the authors have derived dimensionless power output, energy/exergy efficiency and dimensionless irreversibilities of the thermoelectric generator and then analysed the effect of annular shape factor (S_r), dimensionless temperature ratio (θ-theta) and load resistance ratio (R_L/R_o) on the performance of ATEG system.

2. Thermodynamic modelling of ATEG

A typical ATEG with two thermoelectric couple is shown in Fig. 1, unlike flat plate thermoelectric generator the cross section area $A(r)$ of the thermoelectric couple increases in the radial direction (r).

Certain assumptions were made in the thermodynamic modelling and analysis of ATEG, that are as follows:

- One dimensional steady state heat transfer along the radial direction is considered for the analysis.
- The thickness (δ) of the thermoelectric couple is constant.
- Convection heat transfer from the sides of thermoelectric couples to the environment is neglected.
- The electrical and thermal contact resistances are assumed to be 10% of the electrical and thermal resistances of the thermoelectric couple.

The temperature dependent properties of thermoelectric material (Bismuth Telluride – Bi_2Te_3) used in this study are given below as provided by Xuan et al. [37].

$$\alpha = [\alpha_p - (-\alpha_n)] = 2 \times (22224.0 + 930.6T_m - 0.9905T_m^2) \times 10^{-9} \quad (1)$$

$$\rho_n = \rho_p = (5112.0 + 163.4T_m + 0.6279T_m^2) \times 10^{-10} \quad (2)$$

$$k_n = k_p = (62605.0 - 277.7T_m + 0.4131T_m^2) \times 10^{-4} \quad (3)$$

$$\tau = [\tau_p - (-\tau_n)] = 2 \times \left(930.6T_m - 1.981T_m^2\right) \times 10^{-9} \quad (4)$$

Cross section view of the annular thermoelectric generator is shown in Fig. 2. Applying first law of thermodynamics the energy balance in an infinitesimal element (dr) of the ATEG can be written as follows:

$$Q_{storage} = Q_r - Q_{r+dr} + Q_{gen} - Q_{loss} \quad (5)$$

The thickness of the thermocouple (δ), width ($\Delta\varphi$) in the radial direction is assumed to be constant and small, and the length of the thermocouple ($dr = r_2 - r_1$) is also small. Therefore, the thermal energy stored ($Q_{storage}$) in the thermoelectric leg is neglected. Based on the assumptions ($Q_{storage} = Q_{loss} = 0$). Q_r and Q_{r+dr} are the heat input and output to the small elemental section dr and Q_{gen} is the sum of Thomson and Joule heat generated in the elemental section (dr).