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Energy and exergy analysis of solar heat pipe based annular thermoelectric generator system

S. Manikandan, S.C. Kaushik

Centre for Energy Studies, Indian Institute of Technology Delhi, India

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ABSTRACT

In this paper, the energy and exergy analysis of the solar annular thermoelectric generator (SATEG) considering Thomson effect in conjunction with Peltier, Joule and Fourier heat conduction have been introduced. Unlike the flat plate thermoelectric generator, the cross section area of an annular thermoelectric generator increase along the radial direction. Therefore, the annular thermoelectric generator possess higher total heat transfer area when compared with flat plate thermoelectric generator. The solar radiation absorbed by the solar heat pipe is given as the energy input to the SATEG. This system has the advantage of providing electrical power output and hot water output. The results of this study show that the power output and overall exergy efficiency of the SATEG are 1.92 W and 5.02% respectively and are 0.52% and 0.40% higher than that of solar flat plate thermoelectric generator (SFTEG). SATEG system has advantage of better thermal insulation, improved heat transfer characteristics, easy installation and maintenance when compared with the solar flat plate thermoelectric generator because of its cylindrical structure. This study will be helpful in designing of actual solar annular thermoelectric generation systems.

1. Introduction

Thermoelectric power generation is a solid state direct energy conversion technique for converting heat into electricity (Angrist, 1965; Goldsmid, 1986; Rowe, 1995). It operates on the principle of Seebeck effect. When two different metals are connected to form a closed circuit, and the two metal junctions are kept at different temperatures, electric current will flow because of difference in Fermi energy levels at two junctions.

Thermoelectric generator works as a heat engine operating between the two heat reservoirs and its actual efficiency is much 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 no maintenance, offer noiseless operation with light weight and compactness (Mathiprakasam, 1993). Thermoelectric devices have better efficiency at lower power level as compared with the conventional thermodynamic devices for power generation and space conditioning. Therefore, these devices are best suited for low power applications (Vining, 2009).

Agrawal and Menon (1997) considered the thermoelectric generator as an endoreversible heat engine and compared thermoelectric generator with Curzon–Ahlborn engine. Chen et al. (2002) studied the thermoelectric generator with heat transfer irreversibilities and found that the heat transfer irreversibilities have influence on the performance of the thermoelectric system. Chen et al. (2007) optimized the heat transfer area of the thermoelectric generator for maximum power output and energy efficiency conditions. It was also observed that the working electric current and heat transfer area have more effect on the performance of the thermoelectric generator system.

Thermodynamic analysis in the multi couple thermoelectric generator have been carried out by Chen et al. (2000) and Pan et al. (2007). Wang et al. (2012) studied the design of air cooled heat sink to maximize the performance of thermoelectric generator by two stage optimization technique and found that the performance can be improved by modified design of heat sink.

Chen et al. (1996) studied the impact of Thomson effect in the energy efficiency and power output of a single stage flat plate thermoelectric generator system and found that the Thomson effect reduces the power output and energy efficiency considerably. Huang et al. (2005, 2006) and Chen et al. (2012) studied the influence of the Thomson effect in the single stage thermoelectric cooler system and found that the Thomson effect affects the temperature profile of the thermoelectric leg and it may increase

E-mail addresses: manikandan@ces.iitd.ac.in (S. Manikandan), kaushik@ces.iitd.ac.in (S.C. Kaushik)

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Nomenclature

a	absorptivity
h	heat transfer coefficient (W/m^2)
r	radius (m)
t	transmissivity
A	area (m^2)
Ex	exergy (W)
G	solar radiation (W/m^2)
I	current (A)
Irr	irreversibility (W)
K	thermal conductance (W/K)
P	electrical power (W)
Q	heat (W)
R	electrical resistance (Ω)
T	temperature (K)
Z	figure of merit (1/K)

Greek letters

Δ	difference
Ψ	exergy efficiency
α	Seebeck coefficient (V/K)
δ	thickness (m)
ε	emissivity
η	energy efficiency
θ	dimensionless temperature
k	thermal conductivity (W/m K)
ρ	electrical resistivity (Ω m)
σ	Stefan Boltzmann constant (W m^{-2} K^{-4})
τ	Thomson coefficient (V/K)
φ	angle

Subscripts

1	inner
2	outer
abs	absorber (heat pipe)
air	environment
c	cold side of TEG
cover	heat pipe outer cover
el	electrical
dr	infinitesimal
gen	generation
h	hot side of TEG
hp	heat pipe
in	input
loss	loss
m	mean
N	n type material
O	reference
out	output
P	p type material
r	radius
rad	radiation
storage	storage
sys	combined system
th	thermal
tube-in	absorber tube
tube-out	outer tube/cover
water	water

the cooling power and energy efficiency of the thermoelectric cooler system. Rabari et al. (2015) and Xiao et al. (2011) studied the effect of convection heat transfer in a single stage flat plate thermoelectric generator (FTEG) 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 (2015) studied the thermoelectric generator operated thermoelectric cooler combined system for low cooling power applications with maximum power point tracking technique and found that the maximum power point tracking technique will improve the power output, cooling power and system efficiency of the thermoelectric generator–thermoelectric cooler combined system.

Sahin and Yilbas (2013) and Ali et al. (2014) studied the thermoelectric couple with trapezoidal geometry and found that the energy conversion efficiency is higher than the flat plate geometry of thermoelectric couple but the power output is lesser than the flat plate thermoelectric couple. Shen et al. (2015) studied the annular thermoelectric generator (ATEG) without considering the Thomson effect and found that the energy efficiency of ATEG is lower when compared with FTEG. Kaushik and Manikandan (2015) studied the influence of Thomson effect in the power output, energy and exergy efficiency of an annular thermoelectric generator and found that the Thomson effect reduces the power output, energy and exergy efficiency of annular thermoelectric generator. Bauknecht et al. (2013) studied the performance inhomogeneity in a ring shaped thermoelectric couples with various flow 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.

Kaushik et al. (2015) have performed detailed exergy analysis of a thermoelectric generator 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 consideration both the first and second law of thermodynamics. With exergy analysis technique the actual exergy destruction in the system can be located so that the avoidable exergy losses can be reduced by taking corrective measures (Dincer and Rosen, 2012; Telkes, 1954).

Solar thermoelectric generator systems have been analysed thermodynamically by various authors from time to time (Amatya and Ram, 2010; Xiao et al., 2012; Goldsmid et al., 1980; Eswararmoorthy and Shanmugam, 2010; Shanmugam et al., 2011; Baranowski et al., 2012; Chen et al., 2014; Candadai et al., 2016). Jafarkazemi et al. (2015) studied the solar evacuated tube collector, and calculated its energy and exergy efficiency. Recent developments in evacuated tube solar collectors have been reviewed by Sabiha et al. (2015). He et al. (2012, 2011) theoretically and experimentally studied the evacuated tube collector based solar thermoelectric generator using flat plate thermoelectric couples and compared the power conversion efficiency with organic Rankine cycle (ORC) system. It is found that the efficiency of solar thermoelectric generator system is lower than the ORC system but have the advantages of simplicity, no moving parts and easy maintenance. Zhang et al. (2013) studied solar thermoelectric co-generator theoretically and experimentally with solar heat pipe and flat thermoelectric generator and found that, it can simultaneously supply electric power output and hot water to regions where the electric grid is out of reach.

1.1. Proposed methodology

Based on the literature review, it was found that, all the studies in the solar thermoelectric generator systems have been carried