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Theoretical and experimental estimation of limiting input heat flux for thermoelectric power generators with passive cooling

Ashwin Date [a,*], Abhijit Date [a], Chris Dixon [a], Randeep Singh [b], Aliakbar Akbarzadeh [a]

[a] Energy Conservation and Renewable Energy, School of Aerospace Mechanical and Manufacturing Engineering, RMIT University, Bundoora East Campus, Australia

[b] Fujikura Ltd., Thermal Engineering Division, 1-5-1 Koto-Ku, Kiba, Tokyo, Japan

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Abstract

This paper focuses on theoretical and experimental analysis used to establish the limiting heat flux for passively cooled thermoelectric generators (TEG). 2 commercially available TEG's further referred as type A and type B with different allowable hot side temperatures (150 °C and 250 °C respectively) were investigated in this research. The thermal resistance of TEG was experimentally verified against the manufacturer's specifications and used for theoretical analysis in this paper. A theoretical model is presented to determine the maximum theoretical heat flux capacity of both the TEG's. The conventional methods are used for cooling of TEG's and actual limiting heat flux is experimentally established for various cold end cooling configurations namely bare plate, finned block and heat pipe with finned condenser. Experiments were performed on an indoor setup and outdoor setup to validate the results from the theoretical model. The outdoor test setup consist of a fresnel lens solar concentrator with manual two axis solar tracking system for varying the heat flux, whereas the indoor setup uses electric heating elements to vary the heat flux and a low speed wind tunnel blows the ambient air past the device to simulate the outdoor breezes. It was observed that bare plate cooling can achieve a maximum heat flux of 18,125 W/m^2 for type A and 31,195 W/m^2 for type B at ambient wind speed of 5 m/s while maintaining respective allowable temperature over the hot side of TEG's. Fin geometry was optimised for the finned block cooling by using the fin length and fin gap optimisation model presented in this paper. It was observed that an optimum finned block cooling arrangement can reach a maximum heat flux of 26,067 W/m^2 for type A and 52,251 W/m^2 for type B TEG at ambient wind speed of 5 m/s of ambient wind speed. The heat pipe with finned condenser used for cooling can reach 40,375 W/m^2 for type A TEG and 76,781 W/m^2 for type B TEG.

Keywords: Limiting heat flux; Conventional heat sink; Thermoelectric generator; Passive heat sink

1. Introduction

Thermoelectric devices can be used as heat pumps using the Peltier effect or as heat engines for power generation using the Seebeck effect (Rowe, 2006; Gurevich and Logvinov, 2005). Thermoelectric power generators (Seebeck effect) have recently attracted many researchers because of their static operation, environmentally friendly nature, high reliability and potential for generating electricity from lower grade heat sources (Simons et al., 2005; Wang et al., 2012). A thermoelectric generator is a static heat engine that generates voltage when a temperature difference is created across its hot side and cold side. In 1961, the National Aeronautics and Space Administration

* Corresponding author at: Energy Conservation and Renewable Energy Group, School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, PO Box: 71, Bundoora East Campus, Bundoora, Victoria 3083, Australia. Tel.: +61 425 819 090; fax: +61 3 9925 6108.

E-mail address: ashwin.date@studuent.rmit.edu.au (A. Date).

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Nomenclature

Symbols

A	area (m^2)
c	fin gap (m)
h	convection heat transfer coefficient (W/m^2 K)
h^*	modified convection heat transfer coefficient (W/m^2 K)
H	direct incident solar radiation flux on the surface (W/m^2)
I	current (A)
k	thermal conductivity (W/m K)
l	length (m)
q''	heat flux (W/m^2)
$\dot{q}$	total rate of heat flow (W)
R	thermal resistance (°C/W)
th	thickness (m)
T	temperature (K)
V	voltage (V)
v	velocity (m/s)
$\dot{v}$	volume flow rate (m^3/s)
w	width of the fin (m)
$\dot{W}$	power generated (W)
x	height (m)

Greek symbols

ε	emissivity of target and base surface
η	efficiency

Dimensionless numbers

GC	geometric solar concentration
N	quantity
Nu	Nusselt number
Pr	Prandlt number
Re	Reynolds number

Subscripts

a	aperture
b	base
gap	gap between all fins
$conv-tar$	convection from target
$conv-HS$	convection from heat sink
fin	fin
hs	heat sink
in	input
$lens$	fresnel lens
$lost-t$	lost from target
t	target
teg	thermoelectric generator
$rad-HS$	radiation from heat sink
$rad-tar$	radiation from target
∞	ambient

Constants

σ	Stefan Boltzmann constant $\left(5.67 \times 10^{-8} \frac{W}{m^2K^4}\right)$

was the first organisation to use thermoelectric technology in a real application, to supply electrical power to a spacecraft (Ewert et al., 1998). However the use of thermoelectric generators in mainstream power generation is restricted due to its low conversion efficiency of thermal energy to electricity. Many researches around the world are working in the field of materials to improve the conversion efficiency (figure of merit) of TEG's such that they can compete with conventional heat engines (Dresselhaus et al., 2007; Snyder and Toberer, 2008; Hsu et al., 2004; Poudel et al., 2008). At the same time there have been various studies about the use of thermoelectric generators for power generation using different heat sources and cooling techniques. Champier et al. (2011, 2010) has discussed the possibility of generating power using heat sourced from a biomass stove and a wood stove in his paper, while Meng et al. (2011) has investigated the effect of irreversibility's on the performance of thermoelectric generators. Baranowski et al. (2012) and Li et al. (2010) have done a study on potential use of concentrated solar thermal systems to be incorporated with thermoelectrics for power generation with active cooling methods. Most commonly used techniques for solar concentration are parabolic trough & dish, Fresnel lens reflectors and solar power towers (Price et al., 2002; Kritchman et al., 1979). Heat collected from the concentrated solar radiation over the target area results in high temperature heat source used to drive a thermoelectric generator. Heat is rejected to a cold reservoir or a heat sink. By lowering the temperature of the heat sink the efficiency of the heat engine improves. Yazawa et al. (2012) has discussed the thermal challenges in such systems and proposed the small scale residential system in his research. Fan et al. (2011) has done some work on concentrated solar thermal (CST) systems to be combined with thermoelectric generators for energy production with active water cooling heat exchanger. Auxiliary energy consumption by a cooling mechanism in all these systems is a very important component since the conversion efficiency of a commercially available thermoelectric generators is below 5% (Riffat and Ma, 2003). A few researchers such as Singh et al. (2011) and He et al. (2012) have incorporated passive cooling methods for thermoelectric power generation, however they have chosen low heat flux energy sources such as solar ponds or evacuated tube solar collectors.

Previously Date et al. (2011) has presented a theoretical model to determine the limit of solar concentration for