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Thermodynamic studies and maximum power point tracking in thermoelectric generator–thermoelectric cooler combined system

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ABSTRACT

Thermoelectric generator (TEG) operated thermoelectric cooler (TEC) is a highly compatible combination for low-cooling power application. The conventional TEG–TEC combined systems have low operating efficiency and low cooling power because maximum power output from the TEG is not fully utilized. This paper proposes and analyses the combined system with maximum power point tracking technique (MPPT) to maximize the cooling power and overall efficiency. This paper also presents the effect of TEG, TEC source temperature and the effect of heat transfer area in the performance of the combined system. The thermodynamic models of the combined system are developed in MATLAB simulink environment with temperature dependent material properties and analysed for variable operating temperatures. It has been found that, in the irreversible thermodynamic model of the combined system with MPPT, when the hot and cold side of TEG and TEC are kept at a temperature difference of 150 K and 10 K respectively, the power output of TEG increases from 20.49 W to 43.92 W, cooling power of TEC increases from 32.66 W to 46.51 W and the overall combined system efficiency increases from 2.606% to 4.375% respectively when compared with the irreversible combined system without MPPT. The characteristics improvements obtained by this practice in the combined system for the above mentioned operating conditions is also true for other range of operating temperatures. It is also been observed that the external irreversibilities decreases the cooling power and the overall system efficiency of the combined system by 36.49% and by 16.9% respectively.

1. Introduction

In recent years, the thirst 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 as shown in Fig. 1 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, it is clear that the thermoelectric devices are best suited for low power applications [5].

The electrical power output of single thermoelectric couple is low and can be increased by adding thermoelectric couples in series–parallel combination to the required level. Thermoelectric cooler works on the principle of Peltier effect. It absorbs energy at one junction therefore, cooling the space near that junction and releases energy at another junction therefore, heating that junction when quantum of electric current flows through it. Vella et al. [6] stated that the thermoelectric cooler requires low voltage and high current for its operation and therefore, the thermoelectric cooler operated by a thermoelectric generator can be a better combination to produce cooling at one end by heating at the other end of the device. This combination of the thermoelectric cooler operated by thermoelectric generator is called as combined thermoelectric (CTE) system [7]. The merits of the CTE system are, it is a solid state device with no moving parts, it requires lesser maintenance, and it can utilize waste heat to produce cooling.

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Nomenclatures

x	ratio of number of thermocouples in TEG to the total number of thermocouples in combined system
A	area
COP	coefficient of performance
D	duty cycle
I	current
K	thermal conductance
L	length
P	electrical power
Q	heat
R	electrical resistance
T	temperature
U	overall heat transfer coefficient
V	voltage
Z	figure of merit

Greek letters

α	seebeck coefficient
η	efficiency
k	thermal conductivity
ρ	electrical resistivity
σ	electrical conductivity
Δ	difference

Subscript

c	cooler
cc	cold junction of TEC
Cc	cold side of TEC
ce	ceramic layer
cg	cold junction of TEG
Cg	cold side of TEG
DC/DC	DC/DC Converter
g	generator
hc	hot junction of TEC
Hc	hot side of TEC
hg	hot junction of TEG
Hg	hot side of TEG
in	input
irr	irreversible
l	load
m	mean temperature
n	n type material
opt	optimum
out	output
overall	all inclusive
p	p type material
t	total
tec	thermoelectric cooler
teg	thermoelectric generator

The efficiency of the thermoelectric devices depends on electrical conductivity (σ), thermal conductivity (k), and seebeck coefficient (α) of the thermoelectric material. The combination of these material properties of a thermoelectric material is defined as figure of merit (FOM) Rowe [3]. It has the unit of ($1/K$) as shown in Eq. (1). FOM is often defined as dimensionless figure of merit by multiplying it with mean operating temperature (T_m).

$$Z = \frac{\alpha^2 \sigma}{k} \tag{1}$$

$$ZT_m = \frac{\alpha^2}{\rho k} T_m \tag{2}$$

where $T_m = \frac{T_H + T_C}{2}$

To understand the reversible and irreversible effects in thermoelectric systems, one can classify them thermodynamically into four categories based on the irreversibilities in the system such as ideal (or) reversible system, exoreversible system, endoreversible system, and irreversible system as shown in Fig. 2. Since thermoelectric material has its inherent electrical resistivity (ρ) and thermal conductivity (k) so any thermoelectric systems always have internal irreversibilities because of the intrinsic material properties. Super conductors have very low electrical resistivity but its electrical/thermal conductivity is high, and its seebeck coefficient is also very small so its figure of merit will be very low and hence they may not be potential thermoelectric materials. There-

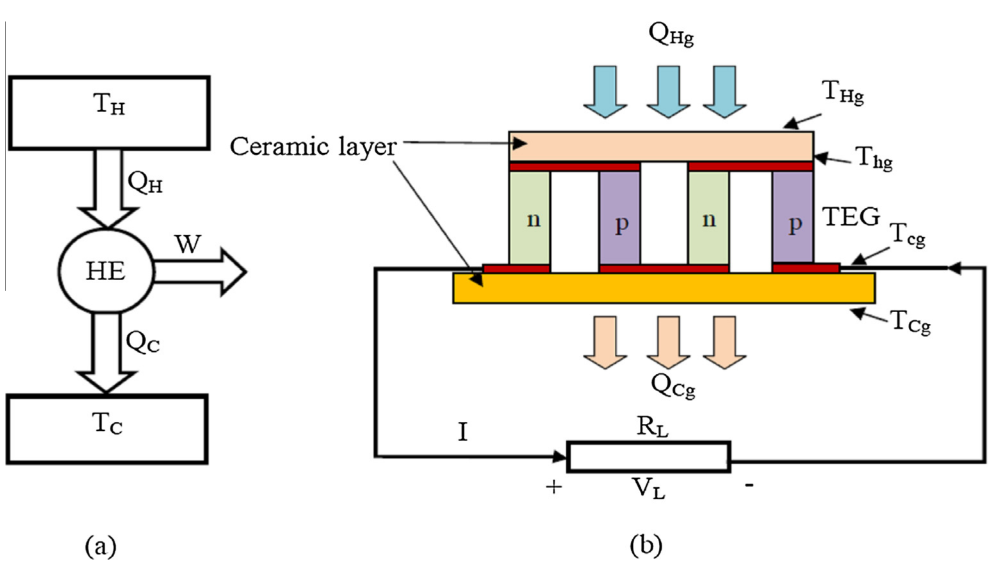

Fig. 1. (a) Heat engine and (b) thermoelectric generator.