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The influence of Thomson effect in the performance optimization of a two stage thermoelectric cooler

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ABSTRACT

The exoreversible and irreversible thermodynamic models of a two stage thermoelectric cooler (TTEC) considering Thomson effect in conjunction with Peltier, Joule and Fourier heat conduction effects have been investigated using exergy analysis. New expressions for the interstage temperature, optimum current for the maximum cooling power, energy and exergy efficiency conditions, energy efficiency and exergy efficiency of a TTEC are derived as well. The number of thermocouples in the first and second stages of a TTEC for the maximum cooling power, energy and exergy efficiency conditions are optimized. The results show that the exergy efficiency is lower than the energy efficiency e.g., in an irreversible TTEC with total 30 thermocouples, heat sink temperature (T_H) of 300 K and heat source temperature (T_C) of 280 K, the obtained maximum cooling power, maximum energy and exergy efficiency are 20.37 W, 0.7147 and 5.10% respectively. It has been found that the Thomson effect increases the cooling power and energy efficiency of the TTEC system e.g., in the exoreversible TTEC the cooling power and energy efficiency increased from 14.87 W to 16.36 W and from 0.4079 to 0.4998 respectively for ΔT_C of 40 K when Thomson effect is considered. It has also been found that the heat transfer area at the hot side of an irreversible TTEC should be higher than the cold side for maximum performance operation. This study will help in the designing of the actual multistage thermoelectric cooling systems.

1. Introduction

A thermoelectric cooler is a solid state direct energy conversion device, which converts electrical energy into heat [1–4]. It operates on the combination of Seebeck, Peltier and Thomson effects. The thermoelectric cooler has the advantage of being a solid state device, with no moving parts and it requires no maintenance. It provides noiseless operation and offers light weight, compactness and it occupies a small space [5].

The thermoelectric devices have better efficiency at low power levels compared with the conventional thermodynamic devices, used in power generation and space conditioning. Therefore, the thermoelectric devices are best suited for low power applications [6]. The two stage thermoelectric coolers are used for point cooling applications with the higher temperature differentials (ΔT_C). Min et al. [7] investigated the performance of the thermoelectric devices with a large temperature differential (cascaded and segmented thermoelectric devices) and concluded that the influence of Thomson effect in the figure of merit of a segmented thermoelectric device is more than that of the cascaded thermoelectric devices. Chen et al. [8] studied the single stage thermoelectric cooler and calculated specific cooling loads for different thermodynamic models. Chen et al. [9] performed theoretical modeling and experimentally verified the performance parameters of the single stage thermoelectric refrigerator. Luo et al. [10] and Meng et al. [11] studied the effect of heat transfer area for optimum coefficient of performance and the effect of irreversibilities in a single stage thermoelectric refrigerator. Chen et al. [12–15] performed an optimization study in a two stage thermoelectric generator, heat pump and cooler systems without considering Thomson effect and optimized the number of thermocouples in the first and second stages. Meng et al. [16,17], Manikandan and Kaushik [18] studied the thermoelectric refrigerator and thermoelectric generator combined system thermodynamically and calculated the working temperature differences and performance parameters for different number of thermocouples in the thermoelectric generator and refrigerator. Chen et al. [19,20] studied the effect of heat transfer area and heat source temperature in thermoelectric generator driven thermoelectric cooler combined system. Meng et al. [21–23] thermodynamically studied the two stage thermoelectric generator driven two stage thermoelectric cooler without considering Thomson effect and optimized the number of thermocouples in the first and second stage of the combined system. Various researchers

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Nomenclature

m	number of thermocouple in the second stage
n	number of thermocouples in the first stage
ξ	ratio of the number of thermocouples in the first stage to the number of thermocouples in the second stage
A	area (m^2)
Ex	exergy (W)
I	current (A)
Irr	irreversibilities (W)
K	thermal conductance (W/K)
L	length (m)
M	total number of thermocouples in a two stage thermoelectric cooler
P	electrical power (W)
Q	heat (W)
R	electrical resistance (Ω)
S	entropy (W/K)
T	temperature (K)
U	overall heat transfer coefficient (W/m^2 K)
Greek letters	
α	Seebeck coefficient (V/K)
η	energy efficiency
k	thermal conductivity (W/m K)
ρ	electrical resistivity (Ω m)
Δ	difference
Ψ	exergy efficiency
Subscripts	
1	hot junction of the first stage
2	cold junction of the second stage
c	cooler
ce	ceramic layer
eff	energy efficiency
ex	exoreversible TTEC
gen	generation
in	input
ir	irreversible TTEC
lost	lost
m	interstage
n	*n* type material
o	environment
out	output
p	*p* type material
*C*1	input to stage 1
*C*2	input to stage 2
*H*1	rejected stage 1
*H*2	rejected stage 2
Qc	cooling power

[24–30] optimized the single and multiple stage thermoelectric devices, based on non-equilibrium thermodynamics and finite time thermodynamics. Chen et al. [31] studied the influence of Thomson effect in the performance of a single stage thermoelectric generator. Huang et al. [32] also investigated the performance of a single stage thermoelectric cooler taking into consideration Thomson effect. These studies are based on energy analysis using first law of thermodynamics.

Exergy analysis provides the true measure of energy efficiency since it takes into consideration of both the first and second laws of thermodynamics. With this technique, the actual exergy losses can be located in the system so as to reduce the avoidable exergy losses by taking corrective actions [33–37]. Exergy analysis in the single and two stage exoreversible thermoelectric cooler and heat pump, has been addressed without Thomson effect by some researchers [38–41]. Since, ΔT_C is large, the influence of the Thomson effect will be more pronounced in the performance of a TTEC, but no optimization studies were available in literature in a TTEC considering Thomson effect.

1.1. Proposed methodology

Based on the literature search, it is clear that the influence of Thomson effect in a two stage thermoelectric cooler is not studied. It is clear from [7] that, if large temperature difference present between the hot and cold junction of a thermoelectric device, the Thomson effect should be considered. It should be noted that the temperature difference between the hot and cold junctions of two stage thermoelectric cooler is higher than the single stage thermoelectric cooler. Therefore, the influence of Thomson effect in two stage thermoelectric cooler should be considered in optimizing the number of thermocouples in its first and second stage for maximum cooling power and efficiency conditions. Moreover, there are no studies available in literature for evaluating the exergy efficiency of a two stage thermoelectric cooler considering Thomson effect.

In this paper, the influence of Thomson effect in the performance of a TTEC has been examined using exergy analysis. The exoreversible and irreversible thermodynamic models of a TTEC are built considering Thomson effect, in conjunction with Peltier effect, Joule heating, Fourier heat conduction and irreversible heat transfer from the hot and cold side of a thermoelectric cooler. The number of thermocouples in the first stage (n) and second stage (m) with fixed total number of thermocouples ($M = n + m$) in a TTEC is optimized for the maximum cooling power, maximum energy and exergy efficiency conditions. The results obtained from this study, will clarify the misconceptions existing in related studies and will give theoretical support for the optimal design of the real two stage thermoelectric coolers.

The performance optimization studies have been carried out considering the Thomson effect and the exergy efficiency of a two stage thermoelectric cooler have been evaluated. These are the novelty and new contributions by the authors.

2. Thermodynamic modeling

An illustrative diagram of a two stage irreversible thermoelectric cooler is shown in Fig. 1. The number of thermocouples in the first stage is (n) and in the second stage is (m). The total number of thermocouples in the TTEC is M ($M = n + m$). Bismuth Telluride (Bi_2Te_3) is used as the thermoelectric material. The temperature dependent material properties of Bi_2Te_3 are given below as specified Xuan et al. [42].

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

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

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

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