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Numerical Simulation of Thermoelectric Refrigeration System Using Mathematical Software

Anshik Singh,[1] Alka Bani Agrawal[2]
[1]ME.Scholar, Department of Mechanical Engineering, UIT-RGPV, Bhopal, India
[2]Prof., Department of Mechanical Engineering, UIT-RGPV, Bhopal, India
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***Abstract*—This study evaluated the performance of thermoelectric refrigeration systems using Bismuth Telluride (Bi-Te), Lead Telluride (Pb-Te), and Tin Selenide (Sn-Se) through MATLAB simulations and finite element modeling. The goal was to analyze the coefficient of performance (COP) across varying temperature differences (ΔT). Results showed COP decreases with increasing ΔT due to thermal losses. Sn-Se outperformed Bi-Te and Pb-Te, with a peak COP of ~2.7%, making it ideal for ambient applications. Sn-Se also absorbed significantly more heat—31.42% more than Bi-Te and 28.42% more than Pb-Te at ΔT = 40 K. Although Pb-Te has a higher Figure of Merit at 400–600 K, Sn-Se proved most efficient at lower temperatures.**

***Index Terms*—Thermoelectric, Peltier effect, Finite element analysis, Figure of Merit.**

I. INTRODUCTION

Recent years have seen significant advancements in thermoelectric systems, primarily as a result of the use of semiconductors and the integration of thermoelectric components into household appliances. Solid-state heat pumps, which transfer heat from one side to another, are what power thermoelectric coolers. Thermal to electrical energy changes, both reversible and irreversible, control this basic process. The Peltier effect is the primary reversible effect. The device's cooling potential is determined by the Peltier effect, whereas the reversible Joule heating and the Fourier effect deteriorate the total cooling performance.

Thermoelectricity was discovered and developed in 1820-1920 in Western Europe, with much of the work centered in Berlin. The first important discovery related to thermoelectricity occurred in 1823. German scientist Thomas Seebeck [1] found that a circuit made from two dissimilar metals and junctions of the same kept at two different temperatures, produces thermoelectric force which is responsible for flow of the current through module. Now this invention is known as Seebeck effect. [1] In 1834, a French watchmaker and physicist, Jean Charles Athanase Peltier [2] invented thermoelectric cooling effect also known as Peltier effect. Peltier stated that electric current flows through two dissimilar metals would produce heating and cooling at the junctions. [2] The true nature of Peltier effect was made clear by Emil Lenz [3] in 1838, Lenz demonstrated that water could be frozen when placed on a bismuth-antimony junction by passage of an electric current through the junction. He also observed that if the current was reversed the ice could be melted. In 1909 and 1911 Altenkirch [3] give the basic theory of thermoelectric. His work explained that thermoelectric cooling materials needed to have high Seebeck coefficients, good electrical conductivity to minimize Joule heating, and low thermal conductivity to reduce heat transfer from junctions to junctions. In 1949 Loffe [4] developed theory of semiconductors thermo-elements and in 1954 Goldsmid [5] and Douglas [5] demonstrated that cooling from ordinary a down to below 0°C was possible. Rowe, [6] shortly after the development of practical semiconductors in 1950's, Bismuth Telluride began to be the primary material used in the thermoelectric cooling [7].

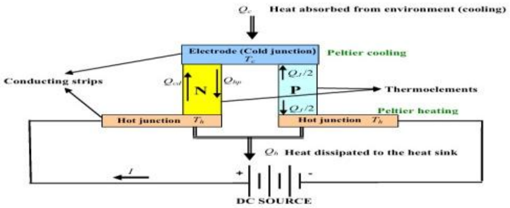


Fig. 1.1 Scheme of a thermoelectric refrigerator.

The Peltier effect is the basis for the thermoelectric cooler; when a voltage or DC current is applied to different materials; it is possible to design a circuit that permits constant heat transfer between the conductor junctions. The Peltier effect is also known as the Seebeck effect. The charge carriers carry the current (either in the opposite direction of the hole flow or in that of the flux of electrons). Depending on the current's direction, heat is transferred. The figure of merit indicates a thermoelectric material's efficiency.

$$Z = \frac{\alpha^2 \sigma}{K}$$

(1)

The Seebeck coefficient (α) is given by Equation 2.

$$\alpha = \frac{E}{\frac{dT}{dX}}$$

(2)

Low thermal conductivity and electrical resistivity are necessary for a high figure of merit in thermoelectric cooler materials. Temperature affects these values. As a result, the temperature affects the figure of merit. The overall quality of P and N-type thermoelectric materials is calculated by averaging their varying figures of merit.

The current study examined a single-parameter thermoelectric module for a one-dimensional steady-state thermoelectric cooling problem, as illustrated in Figure 1. Absolute temperature affects the characteristics of thermoelectric materials. Solid thermoelectric P and N semiconductor materials were determined to be bismuth tellurium (Bi-Te) and antimony tellurium (Sb-Te) with a cross-sectional area of 0.5×0.5mm2 and a length of 0.105mm. Heat is absorbed in the cooling surface, which is kept at temperature Tc, and rejected by the heated surface, which is kept at temperature Th.

Mathematical Formulation of TER System

The temperature difference (DT) at the joint of two different metals resulted in current and created an electromotive force in the executed circuit. This phenomenon, the generated current, and electromotive force were entitled the Seebeck effect, thermo current, and thermo-electromotive force, respectively. The temperature difference (DT) between metal joints can be raised up by raising up the voltage difference (DV). The Seebeck coefficient is a property-based constant and it is different for various materials. It is considered significantly low, about 0mV/K for metals, while this coefficient is regarded much greater for semiconductor materials, 200mV/K. The Seebeck coefficient (a)is defined as

$$\alpha = \frac{\Delta V}{\Delta T}$$

(3)

Thermoelectric refrigerators (TER) utilize thermoelectric coolers (TEC) based on the Peltier effect to remove heat. When a direct current (DC) is applied across two different materials, a temperature difference is created. The performance of TEC can be analyzed in terms of Joule heating, where heat rejection (Qh) from the hot side of the TEC is greater than the heat absorption (Qc) on the cold side. The fundamental equations governing heat absorption and rejection in TEC systems are presented below.

$$Q_c = \alpha I \mathrm{T_c} - 0.5 I^2 R - \kappa_t (\mathrm{T_h} - \mathrm{T_c})$$

(4)

$$Q_h = \alpha I \mathrm{T_h} + 0.5 I^2 R - \kappa_t (\mathrm{T_h} - \mathrm{T}_c)$$

(5)

The Seebeck coefficient (α) is expressed in units of volts per kelvin (VK^1), and represents the thermoelectric potential generated per unit of temperature difference. The electric current (I) drives the thermoelectric cooler (TEC), where (T_c)

and (T_h) denote the temperatures of the cold and hot sides, respectively. The electrical resistance (R) of the TEC material influences the system's efficiency, while the thermoelectric element's thermal conductivity (k) is measured in watts per meter-kelvin ($Wm^{-1}K^{-1}$), governing heat transfer. The coefficient of performance (COP) for both TEC and the thermoelectric refrigerator (TER) is determined using the following equations.

$$COP = \frac{Q_c}{Q_h - Q_c} = \frac{T_c}{T_h - T_c}$$

(6)

A numerical simulation was conducted using MATLAB software, which employs the finite element method to model and analyze the physical system. The static thermoelectric analysis followed a structured approach: first, constructing the physical model, then meshing it, assigning material properties to different regions, setting boundary conditions and loads, solving the equations, and finally, reviewing the results. The thermoelectric system studied comprises a single pair of P-type and N-type semiconductor materials—Tin Selenide (Sn-Se), Bismuth Tellurium (Bi-Te), and Lead Tellurium (Pb-Te)—with a cross-sectional area of 0.6 × 0.6 mm² and a length of 0.5 mm. These thermoelectric elements are positioned between two copper electrodes, each 0.1 mm thick. The material properties of Sn-Se, Bi-Te, and Pb-Te, considered in the calculations with temperature-independent values, are presented in Table 2.1.

Table 2.1. Material Properties

Materials	Seebeck Coefficient (α) [V/K]	Electric Resistivity (ρ) [Ω·cm]	Thermal Conductivity (k) [W/cm·K]	Density (δ) [kg/cm³]	Heat Capacity [J/(kg·K)]
Bismuth Tellurium (Bi-Te)	P: 200e-6	0.9e-5	1.6	77.40e-4	154.4
	N: -200e-6				
Lead Tellurium (Pb-Te)	P: 175e-6	0.8e-5	1.548	81.60e-4	156
	N: -175e-6				
Tin Selenide (Sn-Se)	P: 600e-6	0.169e-8	2.3	89.20e-4	385
	N;600e-6				

II. RESULT & DISSCUSION

To establish a mathematical simulation model for analysis, the MATLAB Simulink is utilized to create the physical environment of the thermoelectric system. The following steps are undertaken for the thermoelectric system analysis: setting GUI preferences, defining the analysis title, selecting element types and options, establishing element coordinate systems, specifying real constants, defining a system of units, and assigning material properties. The MATLAB software incorporates three elements essential for modeling thermoelectric phenomena, ensuring that the element types define the physics of the problem domain.

The variation of the COP for the thermoelectric element with current is shown in Figures 3.1 and 3.2 respectively. It is found that the COP increases till an optimum current is reached, and then decreases with further increase in the current. A maximum COP of 1.1 and 0.92 were obtained for the Bi-Te and Pb-Te systems at 30 K differential temperature.
Fig. 3.1. Variation of COP for Pb-Te system with current.

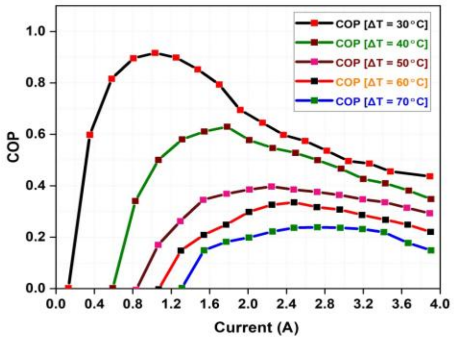
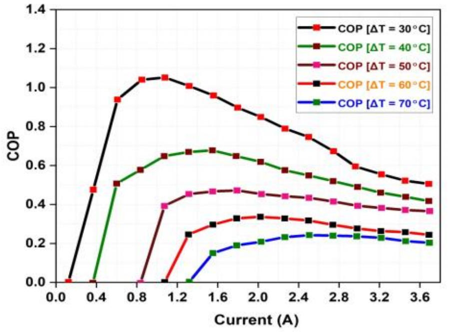


Fig. 3.2. Variation of COP for BI-Te system with current.



The Bi-Te couple has 13.46% higher COP when compared to the Pb-Te couple under the same operating conditions. The optimal COP decreases with an increase in the differential temperature, as shown in figure 3.3. The variation of the optimal current with differential temperature is shown in Figure 3.4. The optimal current for the maximum COP increases with an increase in the differential temperature.

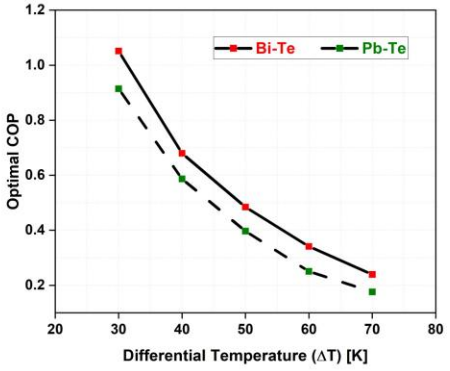


Fig. 3.3 Variation of optimal COP with differential temperature (BiTe – PbTe)

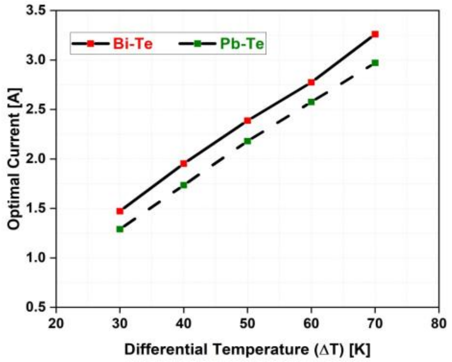


Fig. 3.4 Variation of optimal current with differential temperature (BiTe – PbTe)

III. CONCLUSIONS

Performance Declines with Increasing Temperature Difference – The coefficient of performance (COP) of thermoelectric refrigeration systems decreases as the temperature difference (ΔT) increases, highlighting thermal losses that occur at higher ΔT values.

Comparative COP Analysis – Sn-Se demonstrates the highest COP, outperforming both Bi-Te and Pb-Te under the same operating conditions. Specifically, Sn-Se' COP is 19.46% higher than that of Bi-Te and 13.46% greater than Pb-Te, establishing it as the most efficient option.

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