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Performance Evaluation of Automative Thermoelectric Air Conditioning

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ABSTRACT: The global increase in demand for automotive air conditioning systems significantly impacts vehicle fuel efficiency and contributes to environmental degradation due to greenhouse gas emissions from traditional refrigerants such as CFCs and HFCs. Thermoelectric air conditioning (TEAC) offers an eco-friendly alternative that utilizes the Peltier effect to achieve cooling without the use of harmful refrigerants or mechanical compressors. This paper presents a comprehensive analysis of TEAC systems, focusing on design, implementation, and performance evaluation in automotive applications. Results demonstrate that TEAC systems can effectively reduce cabin temperature while maintaining energy efficiency and lowering environmental impact. This study highlights the feasibility of integrating TEAC into modern vehicles to replace conventional HVAC systems.

KEYWORDS: Thermoelectric Module, Peltier Effect, Seebeck Effect, Automotive Cooling, Eco-Friendly HVAC

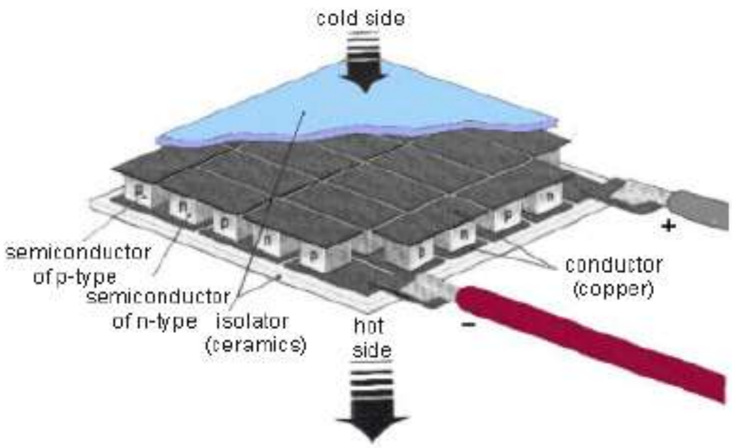
1.INTRODUCTION

The demand for automotive air conditioning systems has been steadily increasing due to the need for passenger comfort and health. Conventional HVAC systems rely on vapor compression cycles that use refrigerants harmful to the environment, such as chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs). These systems contribute to greenhouse gas emissions, ozone layer depletion, and increased fuel consumption in vehicles. Thermoelectric modules (TEMs) offer a sustainable alternative by directly converting electrical energy into thermal energy through the Peltier and Seebeck effects. Unlike conventional compressors, TEMs are compact, silent, and have no moving parts, making them ideal for automotive integration. This paper explores the design and performance analysis of thermoelectric-based air conditioning systems for automobiles.

It is essential to recognize the significant elements of the project and its final outcome. Therefore, it is essential to explicitly articulate and acknowledge the purpose of a project.

To critically analyze the existing HVAC system for its advantages and shortcomings.

- To investigate diverse technological alternatives for the replacement of the current HVAC system.
- To investigate TEC as an alternative to the existing HVAC system, addressing all its shortcomings.
- To construct a functional model of HVAC with a Thermoelectric Cooler (TEC) (Fig:1).
- To evaluate HVAC systems utilizing TEC for their efficacy, efficiency, environmental sustainability, comfort, and convenience.



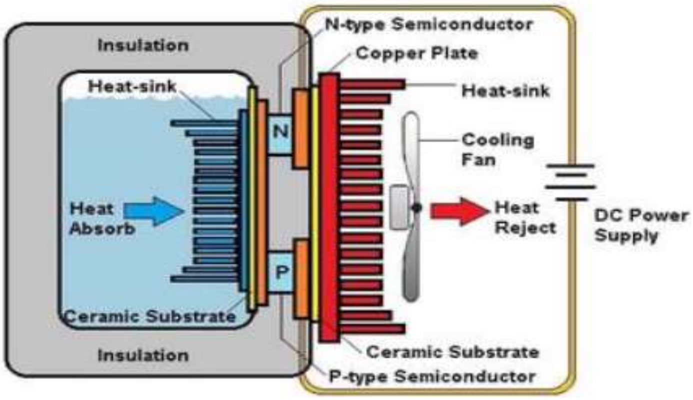


Figure: 1 TEC-AC schematic diagram

2. LITERATURE REVIEW

Previous studies have investigated various approaches to improve automotive air conditioning efficiency. Traditional HVAC systems, while effective, pose significant environmental challenges due to refrigerant emissions. Recent research has focused on thermoelectric cooling systems as an alternative. Studies by Uemura et al. (2021) and Manohar et al. (2021) demonstrated that Peltier-based systems are promising due to their eco-friendliness and reduced maintenance requirements. Gawli et al. (2020) and Singh et al. (2020) highlighted the ability of thermoelectric systems to provide localized cooling in vehicles without relying on refrigerants. Further advancements in thermoelectric materials have improved their coefficient of performance (COP), making them increasingly viable for commercial use (Fig:2).

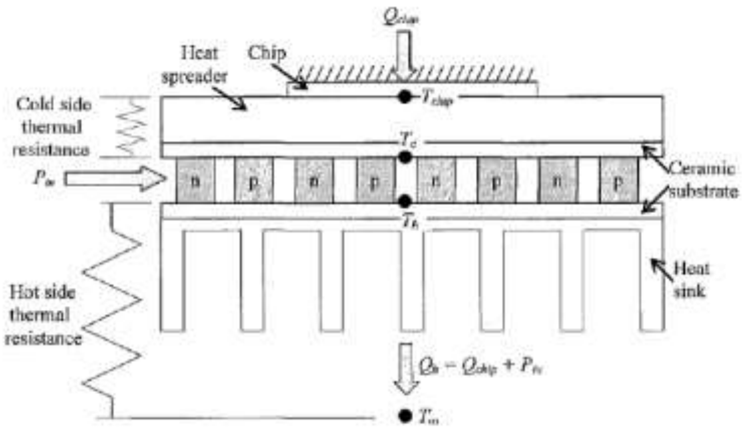


Figure: 2 TEC Thermal Resistance

3. METHODOLOGY

The proposed thermoelectric air conditioning system consists of Peltier modules connected to a heat sink and powered by a DC source. A blower circulates cabin air over the cold side of the module while heat is dissipated from the hot side using forced convection. The design eliminates the need for compressors and refrigerants.

Key components include:

1. Peltier modules (TEC1-12704)
2. Heat sinks for hot and cold sides
3. Blower fan for air circulation
4. DC power supply from the vehicle battery
5. Temperature sensors for system monitoring

Experiments were conducted under varying ambient temperatures to evaluate cooling performance and system COP.

The cooling system primarily comprises the following modules. The car blower serves as the principal source of air.

- Duct that transports air from the blower to cold heat exchangers.
- A single elongated heat sink is affixed to the hot side of the thermoelectric cooler (TEC) to dissipate heat.
- Aluminum heat sinks affixed to the cold side.
- Four thermoelectric coolers are positioned between cold and hot heat sinks.
- A DC supply utilized to power the fans and blower. Automobile Battery
- A DC power supply is utilized to operate the thermoelectric coolers (TECs).

Before initiating the design of a TEC cooling system, the designer must consider the following factors.

1. The temperature must be sustained for the object requiring cooling.
2. Heat to be extracted from the cooled item.
3. Duration necessary to achieve cooling after the application of DC power.

4. Anticipated ambient temperature.
5. Space is allocated for the module and the hot side heat sink.
6. Anticipated temperature of the hot side heat sink.
7. Power accessible for the TEC.
8. Regulating the temperature of the cooled object if required

4. Results and Analysis

Experimental results were collected under three different conditions: morning, afternoon, and evening. The system successfully reduced cabin temperatures across all test conditions. In morning tests with an ambient temperature of 29.5°C, the cabin temperature dropped to 21.5°C within 30 minutes. During afternoon tests (ambient temperature of 42°C), a similar cooling trend was observed, with temperatures reduced to 34°C.

The calculated COP values varied between 0.25 and 0.4, indicating consistent thermoelectric performance. Forced convection heat sinks were found to significantly enhance cooling efficiency compared to natural convection setups.

- Cold side temperature (T_c)
- Hot side temperature (T_h)
- Operating temperature difference (ΔT), which is the temperature difference between Th And Tc .
- Amount of heat to be absorbed at the TEC's cold surface. This can also be termed as heat load. It is represented as (Q_c) and the unit is Watts
- Operating current (I) and operating voltage (V) of the TEC.

The two temperatures, Tc and Th, along with their differential, ΔT, constitute a critical factor. ΔT must be precisely ascertained for the cooling system to function as intended. The subsequent equation illustrates the actual ΔT.

$\Delta T = T_h - T_c$

Actual ΔT is not equivalent to system ΔT. The actual ΔT is the disparity between the hot and cold sides of the thermoelectric cooler (TEC). Conversely, system ΔT represents the temperature differential between the ambient temperature and the temperature of the load requiring cooling. (Teertstra,1999)

4.1 Result Discussions:

Table:1 Time -Temperature conditions inside car in Morning Time

Condition 1:

In Morning hrs., when car parked under shade.

time(min)	temperature inside car
5	32
10	31.8
15	31.1
20	30.7
25	28.8
30	28.3
35	28
40	27.6
45	27.2
50	26.8
55	26.3
60	26

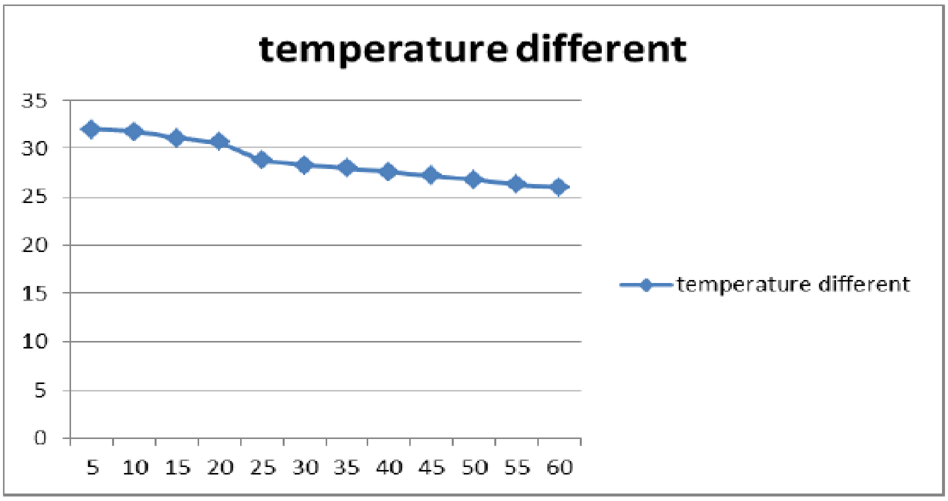


Figure: 3 Time Vs Temperature (Morning)

Table:2 Time -Temperature conditions inside car in Afternoon Time

Condition 2:

At afternoon in peak hours around 1pm to 2pm after TEC running.

time(min)	temperature inside car
5	36
10	35.8
15	35.4
20	35.1
25	34.8
30	34.6
35	34.1
40	33.8
45	33.5
50	33
55	32.7
60	32.3

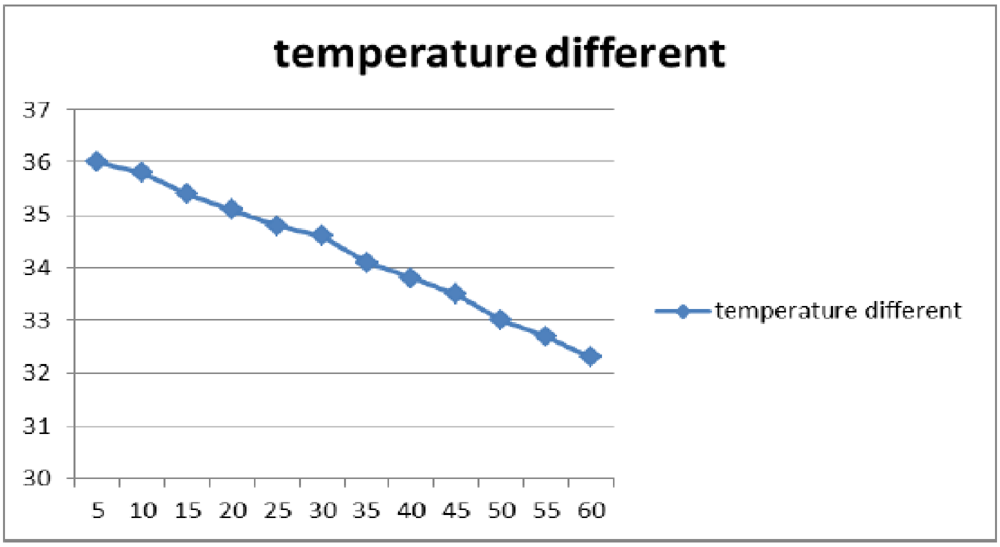


Figure: 4 Time Vs Temperature (Afternoon)

Table:3 Time -Temperature conditions inside car in Evening Time

Condition 3:

In night hours around 8.30pm to 9.30pm.

time(min)	temperature inside car
5	29.5
10	29
15	28.5
20	28.5
25	28
30	27.7
35	27.3
40	26.1
45	25
50	24.1
55	23.6
60	23

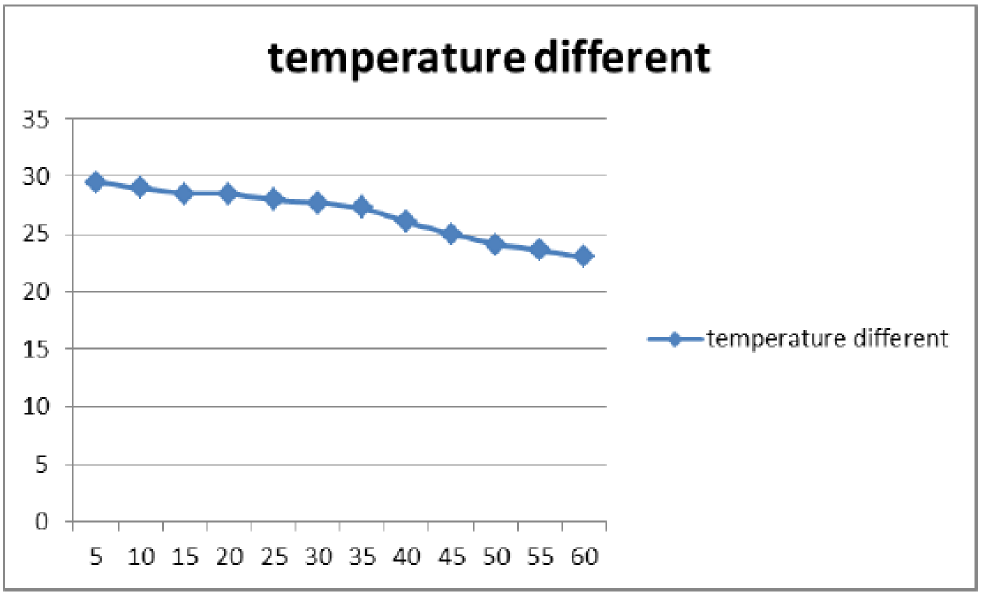


Figure: 5 Time Vs Temperature (Evening)

The cooling power was assessed prior to the selection of the TEC. The quantity of heat absorbed, denoted as Qc, was determined using the equation Qc = ΔT. The mass flow rate of air is the product of the air density and the volume flow rate. The density of air at 32 °C was measured at 1.164 kg/m³. Q was derived by multiplying the velocity of air passing through the rectangular duct of the heat sinks by the cross-sectional area of a heat sink. The equation is represented as Q = V × A. (Venkatasubramanian 2001) The velocity of the air traversing the duct was measured with an anemometer, yielding a measurement of 5.2 m/s. The cross-sectional area of the rectangular duct (W × H) was determined to be 0.0042 m², and the volumetric flow rate was 0.02184 m³/s. The specific heat of air (Cp) at 32 °C is 1005 J/kg·K. The system ΔT represents the difference between the ambient temperature and the temperature of the load requiring cooling. It was aimed to achieve a temperature of 25°C from the ambient temperature of 32°C. The input temperature from the blower fan is 32 °C, while the anticipated output is 25 °C. The difference is calculated as 32 °C - 25 °C = 7 °C.The heat load required for cooling the air via the rectangular duct was determined to be 178.7 W.

Figure 6: Thermo-Electric Air-conditioner

The TEC was chosen based on several variables, including size, Qc, and power supply, among others. The thermoelectric modules utilized in this project were produced in China by Hebei I.T (Shanghai) Co. Ltd. The module's model number is TEC1-12710. The objective was to choose a TEC with a cooling capacity above the computed TEC. TEC1-12710 functions optimally at a voltage of 12V.(TE Tech-2005) The maximum voltage is 15.4V. It draws a maximum DC current of 10 A at 12V. The minimum power rating or cooling capacity is W. The peak power is 96W. The highest operating temperature is 200°C. The temperature differential (ΔT) of the thermoelectric cooler (TEC) is 68°C when the hot side temperature is 25°C. The charts from the TEC manufacturer were also examined during the selection of the TEC. It was determined to select 6 TECs of the identical model to ensure that their combined power exceeds the calculated cooling load. The cumulative minimum power rating for six TECs exceeded the predicted cooling load. Thus, it was permissible to choose 74.5 W × 6 = 447 W, which exceeds 178.7 W. The electrical power provided to the TEC must exceed the cumulative power rating of the six TECs and is contingent upon their configuration. (Muthuraman-2025)

4.2 Temperature Difference

Cooling load (Qc) and thermal resistance calculations as follows

Table:4 Temperature Properties Table

Temperature (°C)	Speed of Sound (m/s)	Density of Air (kg/m³)	Acoustic Impedance (N·s/m³)
+35	351.88	1.1455	403.2
+30	349.02	1.1644	406.5
+25	346.13	1.1839	409.4
+20	343.21	1.2041	413.3
+15	340.20	1.2250	416.9
+10	337.31	1.2466	420.5
+5	334.32	1.2690	424.3
0	331.30	1.2922	428.0
-3	328.25	1.3163	432.1
-5	325.18	1.3413	436.1
-8	322.07	1.3673	440.3
-10	318.94	1.3943	444.6
-12	315.77	1.4224	449.1

4.3 Mass Flow Rate Calculation

Mass flow rate ($\dot{m}$) is given by:

$\dot{m}$ = Density × Area × Velocity

$\dot{m} = 1.1644 \times (0.03 \times 0.14) \times 5.2 = 0.0254$ kg/s

4.4 Heat Absorbed (Qc)

$Qc = \dot{m} \times Cp \times (T1 - T2)$

$Qc = 0.0254 \times 1005 \times (32 - 25) = 178.7$ W

Table:5 Ideal Gas Specific Heat Capacities of Air

Temperature (K)	Cp (kJ/kg.K)	Cv (kJ/kg.K)	k
250	1.003	0.716	1.401
300	1.005	0.718	1.400
350	1.008	0.721	1.398
400	1.013	0.726	1.395
450	1.020	0.733	1.391
500	1.029	0.742	1.387
550	1.040	0.753	1.381
600	1.051	0.764	1.376
650	1.063	0.776	1.370
700	1.075	0.788	1.364
750	1.087	0.800	1.359
800	1.099	0.812	1.354

900	1.121	0.834	1.344
1000	1.142	0.855	1.336
1100	1.155	0.868	1.331
1200	1.173	0.886	1.324
1300	1.190	0.903	1.318
1400	1.204	0.917	1.313
1500	1.216	0.929	1.309

4.5 Thermal Resistance Calculation

Thermal resistance (R) is calculated as:

$R = (\Delta T) / Q$

$Q = 178.7 + 720 = 898.7$ W

$R = (44.3 - 32) / 898.7 = 0.013$ K/W

Therefore, liquid cold convection to be used.

4.6 COP Calculation

Thermal resistance (R) is calculated as:

$COP = Qc/VI$

$COP = 178.7 / 120X6$

$COP = 0.25$

5. Future Scope

Thermoelectric air conditioning systems have potential applications beyond automobiles, including room cooling, aircraft cabins, railway coaches, and portable refrigeration units. Future research should focus on improving thermoelectric material efficiency and integrating energy recovery systems using vehicle exhaust heat to power the thermoelectric modules (Muthuraman-2024) (Fig:7).

Figure: 7 Automative AC -Air Distribution-TEC

6. CONCLUSION

This study demonstrates that thermoelectric air conditioning systems can serve as a viable alternative to traditional HVAC systems in automobiles. By eliminating refrigerants and moving parts, TEAC systems offer environmental and operational benefits. While current COP values are lower than those of vapor compression systems, continuous advancements in thermoelectric materials are expected to enhance performance and adoption in the future.

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