Experimental Analysis of Thermoelectric Device to Produce Cooling Effect Using Solar Energy and Phase Changing Material

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Abstract. This technical paper presents the design and experimental analysis of Thermoelectric Device to produce cooling effect using solar energy as power input. Solar energy is a co2 free renewable energy source. Solar power is an unlimited source of energy. Solar energy is stored in the battery through solar panel. Now the Dc current obtained from solar panel is stored in the battery and is converted into AC current using inverter. Thermoelectric device works on “Thermoelectric effect” which is based on the principles of Peltier effect and Seebeck effect. A model is created to understand the working of thermoelectric effect. Efforts are made in this paper to attain the lower temperature than the surroundings with and without application of phase changing materials. A Phase Changing Material (PCM) is a substance with a high heat of fusion, which is capable of storing and releasing high amount of energy at the time of melting and solidifying at a particular range of temperature. In present work, Formic acid is used as a PCM and results are compared to obtain the optimum process.

Keywords: Peltier effect; Seebeck effect; thermoelectric effect; solar energy; PCM; Formic Acid.

1. Introduction
In today’s world there is an increasing demand for low temperature applications in various fields which led to the increase in utilization of electricity and that devices in turn release more amounts of harmful gases such as CFC’s, CO2. This increase in release of green house gases causes global warming. To minimize these effects, focus is shifted towards the utilization of renewable energy sources. Abundant source of renewable energy on the earth’s surface is solar energy [1]. The new alternative method to produce cooling effect is to design and develop a thermoelectric device powered by solar energy. The thermoelectric modules consists materials made up of semiconductors, which are electrically connected in series configuration and thermally in parallel configuration for creating cool and hot temperatures on either side of the module [2]. Despite the fact that these devices are less efficient compared to conventional refrigerating systems, but they are weightless, cost efficient, less noisy, and are environmentally safe. In addition to this an attempt is made to obtain the lower temperature with the use of phase changing materials (PCM) [3]. A PCM will have lower thermal resistance because of that it will release more amount of heat during liquid to solid phase change and absorb more heat during solid to liquid phase change at the beginning of melting and solidifying process [4].

The main objective of this study is designing and fabricating a working model of thermoelectric device for cooling which employ peltier effect [5] [6], i.e., lowering the temperature at one junction and increasing the temperature at the other junction when electric current is passed in a circuit which consists of two dissimilar conductors; the effect in circuits which contain dissimilar semiconductors is more effective. The model is designed in such a way that the volume inside the cabin should be cooled and maintained within the temperature ranging 7 °C to 22 °C in less period of time and the chillness obtained should remain for at least half an hour. Formic acid, an organic phase changing material is used additionally to achieve the advantages of its charging and discharging processes. During the charging process of the formic acid it absorbs chillness and reaches to its freezing point. When the
power input to the cabin of the thermo electric device is off then the heat enters into the cabin through the TEC module. To avoid this heat absorption into the cabin the formic acid undergoes discharging process so that the temperature inside the cabin can be retained for some time [7]. In this work organic PCM is preferred than inorganic PCMs because organic PCMs are chemically stable, environmentally safe, non-toxic and are non-corrosive in nature [8]. This device can be used in remote locations where generation of electric power is less and uncertain because it is powered from battery which can be charged through solar panel.

To achieve the cooling effect in the model a thermoelectric cooling module (TEC) or peltier cooling module is selected as per calculated cooling load [9] [10]. The internal structure of the peltier element comprises semiconductor pellets fabricated from N-type and P-type Bismuth Telluride materials. The array of pellets is electrically connected in series, but thermally arranged in parallel to maximize thermal transfer between the hot and cold ceramic surfaces of the module. A thermoelectric module comprising a Peltier element sandwiched between two ceramic plates of high thermal conductivity, with a power source, is effectively able to pump heat across the device from one ceramic plate to the other. Moreover, the direction of heat flow can be changed simply by reversing the direction of current flow. Applying a DC voltage causes the positive and negative charge carriers to absorb heat from one substrate surface and transfer and release it to the substrate on the opposite side. Therefore, the surface where energy is absorbed becomes cold and the opposite surface, where the energy is released, becomes hot. The thermoelectric modules must be used with a heat sink.

![Figure1. TEC Module Working](image)

1.1. Literature review
After studying a number of patents on models of thermoelectric devices, solar powered thermoelectric cooling systems are characterised in this section. In 1978 Beitner proposed a simple design which consists of thermoelectric modules powered by an external DC power source and the heat obtained on the hot side is dissipated to the ambient through natural convection. In 1982 Reed and Hatcher indicated an efficient manner to dissipate heat from hot side of TEC to the ambient through forced convection by employing cooling fans. In 1996 Park et al. proposed a new design of thermoelectric refrigerator working with low electrical power supply and also by bringing together the advantages of integrating super insulation materials and PCM’s in thermoelectric system to achieve an environmental friendly device which is capable of saving energy and can retain the obtained temperature uniformly for prolonged periods of time.

2. Objective of the design
Present work aims at designing a model of thermoelectric device for cooling with cabin having a volume of 16L. The device is designed in such a way that temperature range inside the cabin should be in between 7 °C to 15 °C for a specified period of time. The proposed system is solar powered and the device works on DC power stored in the battery, calculation of DC power from voltage and current that is obtained from solar panel at a particular period of time in a day is required. Additionally PCM is used to avoid heat absorption from the TEC module into the cabin when the power is off. As the
system is used in outdoor applications proper care should be taken in providing insulation and radiation control.

3. Steps involved in designing thermoelectric cooling device

3.1. Dimensions of the model. In view of the conditions laid down in the objectives a cubic square cabin is selected with the given dimensions.

| Dimension                        | Details                       |
|----------------------------------|-------------------------------|
| Outer dimensions of the cabin    | 0.30 x 0.30 x 0.30 m          |
| Inner dimensions of the cabin    | 0.25 x 0.25 x 0.25 m          |
| Thickness of aluminium plate    | 2 mm                          |

3.2. Materials. Aluminium sheets which have thermal conductivity of 205W/m-K are used as the inner walls of the vertical side panels. Expanded polystyrene sheets (EPS) which are 50mm thick, 30kg / m³ density and 0.033W/m-K thermal conductivity are used to provide shielding for temperature losses from the cabin. Formic acid with properties as shown in the table 1 is poured into two aluminium boxes of dimensions 16cm×16cm×2cm. These aluminium boxes are attached on the cold side of the TEC module.

| Formula    | Density   | Boiling point | Melting point | Heat of fusion |
|------------|-----------|---------------|---------------|----------------|
| CH₂O₂      | 1.220g/m-L | 101 °C        | 7.8 °C        | 247 ( kJ/kg)   |

3.3. Procedure for designing a thermoelectric device. To design a model of thermoelectric cooling system, the crucial step involves understanding the thermal load concept. Thermal load is the amount of heat energy to be removed from an inner environment. Based on the calculated thermal load, a suitable TEC module is selected for the model. Each TEC module has unique capacity in heat removal process. To achieve required objectives of the design the amount of heat to be removed from the cabin is obtained from the thermal load calculations. After selection of TEC module, the difference in performance of the device without and with the application of organic PCM formic acid is observed.

3.4. Calculation of heat load. Thermal load can be classified as (i) active load and (ii) passive load. In many thermoelectric applications active load can be neglected and therefore there is no need for calculating the active load. Whereas the passive load is defined as a small amount of energy that must be continuously moving in and out of the load to retain a temperature gradient between system and surroundings. In present work the main aim is to maintain the temperature inside the cabin lower than the ambient temperature. Even though utmost care is taken to provide insulation there will be possibility of some leakages in the system. Passive load through the vertical walls is calculated by considering heat transfer components of conduction and convection, from the following equation:

\[ Q_v = \frac{\Delta T A}{\frac{1}{h} + \frac{1}{L K}} \]

Required cabin temperature = 10 °C
Room temperature = 35 °C
Temperature gradient = 35-10= 25 °C
\( K_{AF} = 205 \text{ W/m-K} \);
\( K_{EPS} = 0.033 \text{ W/m-K} \);
\( h_{ae} = 10 \text{ W/m}^2\text{K} \)
Area, \( A_1 = A_2 = A_3 = 0.30 \times 0.30 = 0.09 \text{ m}^2 \)
Passive load through the vertical wall \( Q_{v1} = \frac{\Delta T A}{h_{EPS} L K_{AF}} = \frac{1.562}{10 \times 0.033 \times 205} = 0.911 \text{ W} \)
The passive load through the vertical walls is 
\[ Q_v = Q_{v1} + Q_{v2} = 0.911 + 0.911 = 1.822 \text{ W} \]

For the remaining sides of the cabin the walls contain only EPS and the passive load will be only due to conductive heat transfer.

\[ Q_s = \Delta T \cdot A \cdot K_{EPS} = 0.3125 \times 0.033 = 0.206 \text{ W} \]

\[ Q_s = Q_{s1} + Q_{s2} + Q_{s3} + Q_{s4} = 0.206 + 0.206 + 0.206 + 0.206 = 0.824 \text{ W} \]

Penetration of heat load due to opening and closing of the cabin, \( Q_P \) is approximately 15 W

Total passive load \( Q_{TP} \) = \( Q_v + Q_s + Q_P = 1.822 + 0.824 + 15 = 17.646 \text{ W} \); for safe design, \( Q_{TP} = 25 \text{ W} \)

3.5. Design of the device. The values that are obtained from the calculations needed for the designing of the system are: Heat load \( Q_{TP} = 25 \text{ W} \); Ambient air temperature \( T_A = 35 \text{°C} \); required temperature inside the cabin \( T_C = 10 \text{°C} \). Now with the help of these known values, we have to identify the following:

i. Hot side temperature of the thermoelectric module (\( T_H \))

\[ T_H = T_A + (V \times I + Q) R_T \]

Where, \( T_A \) = Ambient temperature
\( Q \) = Total passive load
\( (V \times I) \) = Thermoelectric module power
\( R_T \) = Thermal resistance (°C/W)

While designing the thermoelectric device, an assumption is made for the heat sink temperature i.e., the heat sink temperature should not go beyond 15 °C more than the ambient temperature. Therefore, the hot side temperature of the thermoelectric module (\( T_H \)) = 35 °C + 15 °C = 50 °C.

Temperature gradient across the thermoelectric module (\( \Delta T \)). The difference of the temperature over the thermoelectric module can be obtained by subtracting the required temperature to be maintained inside the cabin (\( T_C \)) from the hot side temperature of the thermoelectric module (\( T_H \)).

\[ \Delta T = T_H - T_C = 50 \text{ °C} - 10 \text{ °C} = 40 \text{ °C} \]

3.6. Procedure for selection of thermoelectric cooling module (TEC). A TEC module should have the capability to cool and maintain a proper temperature inside the cabin and also the model of the TEC module should cope up with the dimensional constraints of the design. A suitable thermoelectric cooling module is selected, based on the calculated values such as heat load \( Q \), heat losses, temperature gradient (\( \Delta T \)), power input etc. The thermoelectric modules are able to operate in two limit modes:

i. \( Q_{max} \) maximum cooling capacity mode, at \( \Delta T = 0 \);

ii. \( \Delta T_{max} \) maximum object cooling mode, at \( Q_C = 0 \)

More over in practically the combined operation mode is applied. A module’s maximum cooling capacity (\( Q_{cmax} \)) is determined from the formula:

\[ Q_{cmax} = \frac{Q_C \times \Delta T_{max}}{\Delta T_{max} - \Delta T} \]

Where, \( Q_C \) = cooling capacity
\( \Delta T_{max} \) = max temperature difference across the module (72 °C for single stage modules)

Then a TEC module with maximum cooling capacity equal to or greater than the calculated maximum cooling capacity is selected from the TEC module performance data tables. It is observed that module TEC1-12706 meets the design requirements of the device. In present work only 2 TEC modules are
employed to obtain the nominal power rating or the cooling capacity. We can apply more TEC modules for the design to reduce the time taken for acquiring the desired temperature in the cabin.

| Model number | Operating voltage | Maximum Current | Maximum Voltage | Nominal power rating | Couples | Dimensions |
|--------------|-------------------|----------------|----------------|----------------------|---------|-------------|
| TEC1-12706   | 12V DC            | 6 Amp          | 15.4 V         | 92.4                 | 127     | 40 x 40 x 3.5 mm |

3.7. *Selection of heat sink.* Based on the assumption made for the heat sink temperature i.e., the heat sink temperature should not go beyond 15 °C more than the ambient temperature, an effective heat removal system should be employed. Following are the different types of heat sinks: (i) Natural convection heat sink, (ii) forced type convection heat sink and (iii) liquid cooled heat sink. In this work forced convection system i.e., fans are used to drive away the heat from the hot side of the thermoelectric module to the surroundings. Generally the thermal resistance ($R_T$) of the forced convection type heat sinks ranges from 0.10 °C/W to 0.5 °C/W. Substituting the values of $T_A$, $V$, $I$, and $Q$ in the equation $T_H = T_A + (V \times I + Q) \frac{R_T}{R_T}$ and the value of $R_T$ is determined and should be verified if it is in range. $R_T = \frac{(T_H - T_A)}{(V \times I + Q)} = \frac{(50 - 35)}{(12 \times 5 + 17.646)} = 0.1869$ °C/W

Therefore in present design using a TEC1-12706 module employed with a forced convection cooling system meets the required specifications.

4. *Fabrication of thermoelectric device.*
The model with the required dimensions is assembled as shown in the figure. The device is powered from a battery which is charged from the solar energy. A digital thermometer is fixed to check the temperature inside the cabin.

![Figure 2. Model of thermoelectric cooling device](image)

5. *Results and discussions*
5.1. *Solar power.* When panel is fixed position voltages values are taken by using multimeter and ammeter using rheostat and power is calculated from $P=VI$ for different time intervals
Table 3. Calculating DC power from obtained voltage and current

| TIME  | 09:30 | 10:00 | 10:30 | 11:00 | 11:30 | 12:00 | 12:30 | 13:00 | 13:30 | 14:00 | 14:30 | 15:00 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Voltage (V) | 19.93 | 19.95 | 19.90 | 19.85 | 19.94 | 19.92 | 19.93 | 19.81 | 19.77 | 19.80 | 19.63 |
| Current (A)  | 2.47  | 2.74  | 2.50  | 2.51  | 2.50  | 2.47  | 2.36  | 2.15  | 1.98  | 1.93  | 1.65  |
| DC Power (W) | 49.23 | 49.28 | 49.75 | 49.82 | 49.85 | 49.80 | 49.23 | 46.75 | 42.72 | 39.14 | 38.21 | 32.39 |

Total number of cells used in solar panel 54;
Voltage of each cell 0.5 V
Maximum voltage obtained from panel = 54 x 0.5 = 27 V
Capacity of battery used is 12 V - 26Ah
Average current available = 2.3A
Number of hours required to charge the battery = 26/2.3 = 11.3 hrs
Thermoelectric device capacity is 12V - 92W
Current consumed by battery is 6A
Time taken for discharge of battery is 26/6 = 4.3 hrs

5.2. Comparision of time and temperature curves without and with application of PCM Formic acid
The ambient temperature is observed as 35 °C which remains constant. The temperature of the cabin initially i.e., at 0 minutes is observed as 35 °C without and with the application of PCM. The variation of time and temperature is tabulated for every 10 minutes separately. The temperature of the cabin is observed with the help of digital thermometer fixed in the cabin. A graph is drawn between time and temperature with and without application of PCM. It is observed that the time taken for the cabin to cool down with the application of PCM is less when compared to the time taken to cool down without PCM.

![Figure 3. Variation of temperature (y-axis) with time (x-axis)](image-url)
6. Conclusion

Therefore a thermoelectric device is designed successfully for producing cooling effect which fulfills the mentioned objectives. However there are some limitations in this system but it has the advantage of utilising the renewable energy i.e., solar power and the cooling inside the cabin will retain for more time with the help of PCM which made the system energy efficient. In the present work, the cooling effect is produced in the cabin of thermoelectric device with and without the application of PCM. This has a wide range of applications in optoelectronic devices, for storing medicines under controlled temperatures etc. Further improvements can be done in this work like adding metallic foams like copper, aluminium etc to the PCM to enhance its thermal conductivity so that the desired temperature can be obtained in less time and to retain the cooling effect for more time. As renewable energy is used as power input, this device can be used in remote and rural places where there is no electric supply.

References

[1] Swapnil B Patond, Feb 2015 Experimental Analysis of Solar Operated Thermo-Electric Heating and Cooling System (IJETT ISSN: 2231-5381) 20 03
[2] Sujith G, Antony Varghese, Ashish Achankunju, Rejo Mathew, Renchi George and VishnuV, 2016 Design and fabrication of thermoelectric refrigerator with thermosiphon system (IJSEAS ISSN: 2395-3470) 2
[3] Mehling and H Cabeza L.F. Heat and cold storage with PCM. An up to date Introduction into basics and applications (http://www.springer.com)
[4] Kondakkagari Dharma Reddy, Pathi Venkataramaiah and P Praveen kumar, 2015 A Study on Phase Change Material Based Thermal Energy Storage System Using Fuzzy Logic (International Journal of Applied Engineering Research © Research India Publications ISSN 0973 4562) 10 pp 18089-18103
[5] Manoj S Raut and Dr P. V. Walke , May 2012 Thermoelectric Air Cooling For Cars (IJEST ISSN : 0975-5462) 4 05
[6] Siva Kumar N, Agathiyan V, Dhanush S, Gokulnath V and Jagadesh R, 2018 Fabrication of solar refrigeration system by peltier effect (IJARIIE-ISSN(O)-2395-4396) 4
[7] Juan P Trelles and John J Duffy Numerical Simulation of a Porous Latent Heat Thermal Energy Storage for Thermoelectric Cooling (Energy Engg Dept, University of Massachusetts Lowell MA 01854, U. S. A)
[8] Sathiyaraj R, Rakesh R, Mithran N and Venkatesan M Enhancement of heat transfer in phase change material using graphite- paraffin composites (http://creativecommons.org/licenses/by/4.0/).
[9] Sabah A Abdul-Wahab, Ali Elkamel b, Ali M Al-Damkhi, Hilal S Al-Rubai’ey, Abdulaziz K Al-Battashi and Muhammad U Chutani, 2009 Design and Experimental Investigation of portable solar thermoelectric refrigerator (An International Journal for Renewable Energy).
[10] Mayank Awasthi and K V Mali, 2012 Design and development of thermoelectric refrigerator (Int. J. Mech. Eng. & Rob. Res. ISSN 2278 – 0149) 1.