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Design Principles and Performance Evaluation of a Solar PV Operated Thermoelectric Cool Chamber

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Abstract: Thermoelectric coolers utilizing peltier effect offer a promising solution for cooling applications. This study elaborates the design and optimization of a TEC-operated cool chamber and evaluation of developed thermoelectric cool chamber. A number of elements need to be carefully considered during the design process, including heat load assessment, TEC module selection and effective heat dissipation techniques. Appropriate TEC modules are chosen based on estimated cooling load, temperature difference achieved, power consumption, maximum cooling capacity of each TEC and heatsink.

The solar photovoltaic operated thermoelectric cool chamber comprises essential components such as SPV Panel, solar charger controller, battery, PWM controller, TEC module with heat sink, and insulated box (TCC unit). The design considerations involve estimating total power consumption and determining the number and ratings of solar panels, batteries, and power conditioning devices to ensure reliable electricity supply. The system operates on SPV-generated power, utilizing MPPT charge controllers to maximize power output. Pulsed width modulation (PWM) systems efficiently regulate power distribution to thermoelectric modules, optimizing performance. The thermoelectric cool chamber was developed of 40 L water capacity. It was observed that, the chamber and water temperature in developed thermoelectric cool chamber was reduced from initial temperature by 11.85°C and 11.56°C respectively after 24 hours. The chamber and water temperature after 24 hours were 13.31°C and 13.49°C respectively. The performance evaluation showed that the chamber's cooling efficiency was influenced by factors such as cooling load and water volume. This comprehensive approach enables the development of an effective and sustainable thermoelectric cooling system suitable for various applications.

Index Terms- **Cool chamber, evaluation, heat load, solar photovoltaic operated, TEC**

I. INTRODUCTION

Thermoelectricity along with PV generation is alternative renewable option which can be used for cooking, heating, cooling, refrigeration and to obtain comfort workplace environment. Some of the features of Peltier module includes noiseless operation, longer life expectancy, non-generation of harmful gases, compact in size, lightweight, portable, high reliability, low-cost production, less maintenance, viable for outdoor use combined with solar photovoltaic cells, and attractive to use as mini-refrigerator for preserving foods and drugs in small places (Chen *et al.*, 2014 and Afshari *et al.*, 2022). A thermoelectric cooler works on the principle of Peltier effect. The Peltier effect converts the electric current into the temperature gradient and heat transfer occurs from heat source to heat sink by electrons. When a DC flows across the junction of the semiconductors, one side will be cooled, whereas the other is heated depending on direction of current. If electrons flow from p-type to n-type, heat is absorbed in n-type side due to electrons jumping towards a higher energy state. The working principle of peltier thermopile is shown in Fig.1

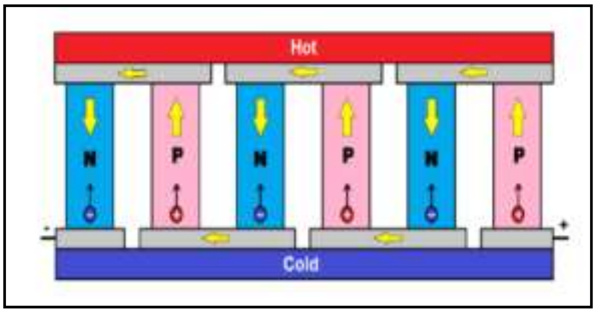

Fig. 1.1 Peltier thermopile

II. METHODOLOGY

2.1 Design of thermoelectric (TEC) cool chamber

The peltier/ thermoelectric/ TEC module was selected by considering cool chamber dimensions, cooling load Q_C, module temperature differential ΔT, power supply etc. In designing a thermoelectric cool chamber, heat was pumped from the cool chamber to the atmosphere. Also, the TEC elements itself generate heat which was added to heat loads. Hence, a poor design may fail to cool. The procedure for designing cooler comprises estimation of total heat load, selecting appropriate TEC modules and heatsink, mounting of TEC assembly with heatsinks.

2.2 Estimation of heat loads in cool chamber

The cooler box was a polyurethane box with inner dimensions 0.64 x 0.35 x 0.39 m (length x width x height) with volume of 0.087 m^3 with perfect fit closing lid on top. The air inside the cold room would absorb the heat from different sources and this heat must be removed in order to maintain the cold chamber at 11°C and 90% relative humidity. The sources of heat load were the transmission through cold room enclosures, infiltrated air from the surrounding, stored product and running equipments like fans, lighting. Based on design specification of the cold chamber and product to be cooled, the equations from the literature could be adapted to appropriately determine the heat load from all sources (Anonymous, 2002; Arora, 2000 and Domkundwar and Arora,1974).

The total heat load was the sum of heat generated inside enclosure due to respiration and cooling of material, radiation, convection and conduction.

$$\begin{aligned} Q_{total} &= Q_{transmission} + Q_{infiltration} + Q_{material} + Q_{fan} \qquad \ldots (2.1) \\ &= 9.62 + 2.67 + 38.70 + 10.8 = 61.79\ W \end{aligned}$$

Where,

$Q_{transmission}$ = Transmission heat load, W

$Q_{infiltration}$ = Heat produced by air changing and leakage air (W)

$Q_{material}$ = Heat produced by material (W)

Q_{fan} = Heat released by operation of fan (W)

The cooling power of a TEC system depended on various parameters, including the working current, temperature difference and geometrical characteristics. TEC modules could be stacked with different number of stages to obtain more cooling power.

2.3 Selecting appropriate TEC

An appropriate TEC was a module which was capable of providing the required cooling power. For this purpose, the manufacturers data sheets and performance graphs of TEC/ peltier modules are used. Palacios *et al.*, (2009); Weera, Sean Lwe Leslie (2014) gave analytical procedure to compute internal parameters from performance curves of thermoelectric modules. These graphs were normalized to provide a universal curve for use with any single or two stage TEC for which the maximum values were known. By using ratios of actual to maximum performance values, performance may be estimated over a wide range of operating conditions. The specification of thermoelectric module (SKHC-7106C) as per datasheet is appended at Table 2.1

Table 2.1. Specification of thermoelectric module (SKHC1-7106C) according to datasheet

Sr. No.	TEC Module type	T_h (°C)	ΔT_{max} (°C)	V_{max} (Voltage)	I_{max} (Current)	Q_{max} (Watts)	AC resistance (Ohms)	Tolerance (%)
1.	SKHC1-07106C	27	72	8.9	6.4	35.6	1.06	±10

Where,

T_h (°C) - Hot side temperature at environment: dry air, N_2

ΔT_{max} (°C) -Temperature difference between cold and hot side of the module when cooling capacity is zero at cold side

V_{max} (Voltage) -Voltage applied to the module at ΔT_{max}

I_{max} (Current) -DC current through the modules at ΔT_{max}

Q_{max} (Watts) -Cooling capacity at cold side of the module under ΔT= 0 °C

AC resistance (Ohms) -The module resistance is tested under AC

Tolerance (%) -For thermal and electricity parameters

The design considerations were chosen based on technical limitations quoted by Basavraj (2020) in order to extend the life of selected peltier modules and so also operation of cool chamber.

2.4 Design considerations for development of solar photovoltaic operated thermoelectric cool chamber

1. Choose the Peltier element with greater heat pump capacity than required ($Q_{max} > Q_c$). This could be achieved using multistage peltier modules or by assembling multiple peltier modules by suitable series/parallel connections. The multistage peltier modules were costlier than single stage peltier modules hence it was decided to assemble multiple peltier modules together.
2. Operating current should be well below I_{max} of the Peltier element in use ($I_{max} > I_{op}$). The most commonly recommended input current for a TEC is 60- 80 % of the I_{max} for that TEC. Input current of greater than 80 % of I_{max} usually resulted in minimal increases in both heat pumping and ΔT while significantly increasing both power consumption and waste heat generated. Input current of lower than 60% (of I_{max}) was also common to create a more efficient system (input power versus heat pumping created).
3. Provision of thermal isolation to the Peltier device to prevent heat transfer from hot side to the cold side should be done with thermal insulation sheet.

4. Either increase the size of the heat sink or add fan to keep the hot side temperature of the Peltier device as low as possible so that ΔT i.e. (T_h -T_c) was favourable for high COP or else the Peltier element would end up drawing more current which was undesirable.
5. The rise of temperature of heat sink should not be more than about 15°C above ambient.

2.5 Installation of TEC assembly

Several methods for installing thermoelectric modules have been developed, including mechanical clamping, epoxy bonding, and direct solder bonding. The mechanical clamping was by far the most common. During assembling of TEC system, thermal resistance should be minimized. All mechanical interfaces between the object kept at cold side and the hot side acted as thermal resistive interfaces. All thermal interfaces tend to inhibit the flow of heat or add thermal resistance (Anonymous, 2007; Anonymous, 2019). TEC was installed with heat sinks at both hot and cold side using thermal grease interfaces (aluminium oxide paste). The modules alongwith heat sinks were surrounded with insulation. Also, within the modules if insulation was not proper, due to temperature gradient, minute water vapours got condensed which would hinder the heat flow.

2.6 Power consumed by thermoelectric cool chamber (Q_t)

The total power consumed by thermoelectric cool chamber with TEC assemblies and fans (Q_t) is given by,

$$Q_t = Q_{TEC} + Q_{fan}$$

$$Q_t = 14.75 + 10.8 = 25.55 \text{ W} \quad \ldots (2.2)$$

2.7 Components of solar photovoltaic operated thermoelectric cool chamber

The developed thermoelectric cool chamber (TCC) comprised of SPV Panel, solar charger controller, battery, Pulse width modulated (PWM) power supply, solar charge/ MPPT controller, thermoelectric module with heat sink and insulated box. The schematic of components assembly of developed thermoelectric cool chamber is shown in Fig. 2.1 respectively.

Fig. 2.1. Schematic of components assembly of developed thermoelectric cool chamber

2.8 Design of solar photovoltaic operated thermoelectric cool chamber

For design of solar photovoltaic operated thermoelectric cool chamber, total power consumption was estimated. The wattage of all components connected to the system were considered for computation. The design of a solar photovoltaic system was about to determine the number and ratings of solar panels, battery and power conditioning devices used to supply reliable electricity to the thermoelectric cool chamber.

The TCC system was designed to run on SPV generated power. The daily solar radiation in Konkan region was 5 kWh/m^2/day or it could be said that equivalent sunshine hours of Konkan was 5 h/day (Pawar *et al.*, 2022 and Sengar *et al.*, 2012). Thus, for 5 hours TCC unit run on DC power source from SPV panel and for remaining 19 hours TCC unit should run on battery. Hence the source comprising SPV modules and Maximum power point tracker (MPPT) charge controller was connected in parallel with battery and TCC unit. The MPPT charge controller ensured maximum amount of generated DC power supply from SPV panels to battery and thermoelectric cool chamber (TCC) unit through PWM. The input to PWM controller was 12V DC from battery and output from it was 10.28V DC to TCC unit.

The pulsed width modulation systems were more efficient, compact and produced less waste heat. The PWM power source had its own resistance and hence though voltage supplied from battery was 12 V, it supplied 10.28 V to the TECs. When single TEC was powered with PWM power supply, it consumed 5.5 A at 10.28 V. The average internal resistance of TEC was 1.78 Ω.

As per the datasheet of selected TEC module SKHC1-07106C, the maximum power rating was limited to 56.96 W at maximum current of 6.4 A. On full power through PWM source, the single TECs measured current and voltage was 5.5 A and 10.28 V respectively. Thus, single TECs operating power was 56.54 W which was almost 85% of maximum power. Similarly, operating current was 86% of I_{max}. According to the heat load estimates, a thermoelectric cool chamber required six TECs to function. Six thermoelectric coolers (TECs) should be arranged so that the thermoelectric cool chamber (TCC unit) operated with higher cooling capacity of TEC and that each TEC operated at less than 80% of I_{max} while using less electricity (Basavraj, 2020). Pathak *et al.*, (2017) reported that maximum decrease in temperature of polystyrene cabinet of thermoelectric refrigerator was found at operating current of 0.5 I_{max}. Thus, it was decided to arrange six TECs -two TECs were connected in series and three such strings in parallel. The power consumed by the TEC assembly with respect to number of TECs is given in Table 2.2.

Table 2.2. Power consumption of TEC assembly at 100% duty cycle of PWM controller

S. N.	No. of TEC Operating	Current, A	Voltage supplied across each TEC, V	Power, W
1.	Single TEC	5.5	10.28	56.54
2.	Two TEC (one pair) connected in series	2.75	2(5.14)	28.27
3.	Six TEC- Three pairs connected parallel	2.87 + 2.75 + 2.82 = 8.44	6(5.14)	86.76

2.9 Load estimation

The thermoelectric cool chamber needs to be powered by the PV system/battery. Energy consumed by thermoelectric cool chamber in a given day was obtained by simply multiplying its power rating by the number of hours of operation (Table 2.3).

Table 2.3. Estimation of daily energy consumed by thermoelectric cool chamber

S. N.	Components	Current, A	Voltage, V	Watt	Nos.	Total Watts, W	No. of hours	Energy, Wh (Total watts x No. of hours)
1.	TEC pair	2.87	10.28	29.50	03	88.51	24	2124.25
2.	Fan (hot side and cold side)	0.15	12	1.8	06	10.8	24	259.20
5.	Recorder	0.012	3.3	0.04	01	0.04	24	0.9610
Thermoelectric cool chamber with fan air cooled heat sink, Total (a)						99.35		2384.41

2.10 Determination of battery size

The battery was chosen to supply the power and energy required by the load and compensate the loss of energy in converter. As the TCC unit and battery were connected in parallel with power source, TCC unit took power directly from source for 5 hrs. Now to run TCC unit for remaining 19 hours on battery, size of battery was determined as follows: Consider the depth of discharge (DOD) for lead acid battery as 70% (Table 2.4).

Table 2.4. Estimation of battery Ah capacity

S. N.	Experimental system	Energy, Wh	System voltage, V	Battery capacity, Ah	DOD, %	Actual capacity, Ah
1.	TCC unit with fan air cooled heat sink	2384.41	12	198.70	70	283.85 ≅ 300

2.11 Determination of PV module size

The solar PV module must supply enough energy to charge battery and run the TCC unit for 5 hours, simultaneously. Thus, for determination of solar PV size, battery efficiency, panel efficiency was considered which is depicted in Table 2.5 to Table 2.7.

Table 2.5. Estimation of daily energy that need to be supplied by PV module.

S. N.	Experimental system	Hourly distribution	Actual capacity, Ah	System voltage, V	Energy, Wh
1.	TCC unit with fan air cooled heat sink	19 hrs	300	12	3600
		5 hrs	10	12	120
				Total (a)	3720

Since, charging and discharging of battery repeatedly caused losses upto 30%. Thus, consider battery efficiency as 70%.

Table 2.6. Estimation of energy to be supplied by PV module to battery

S.N.	Experimental system	Energy, Wh	Battery efficiency, %	Energy to be supplied by SPV, Wh
1.	TCC unit with fan air cooled heat sink	3720	70	5314

2.12 SPV module wattage estimation and module capacity

Considering daily equivalent sunshine for 5 hours, the hourly generated power by SPV was calculated as shown in Table 2.7. Assuming 85% panel efficiency total power generated by SPV system was calculated.

Table 2.7. Estimation of SPV module wattage and sizing

S. N.	Experimental system	Energy supplied by SPV, Wh	Daily equivalent sunshine hours	Hourly generated power, W	Panel efficiency, %	Generated panel power, W	Panel sizing (peak power, no. of panels)
1.	TCC unit with fan air cooled heat sink	5314	5 h	5314/5 = 1062	85	1249.41≅ 1250	340 Wp x 4 OR 250 Wp x 5

Since, 340 Wp and 250 Wp SPV panels were available in the market, required no. of panels was determined. These PV panels were connected in parallel.

2.13 Sizing and choice of electronic components

The electronic components include solar charge controllers (for optimal generation of electricity) or MPPT (to ensure maximum generation of power from panels). Many manufacturers combine function of charge controller and MPPT in one single device called MPPT charge controller. The MPPT charge controller should be chosen as per the required input and output voltage and current of load as shown in Table 2.8.

Table 2.8. Estimation of MPPT rating considering conversion efficiency of 75%

S. N.	Panel wattage, W	Power available at output of MPPT (75%), W	Load voltage rating, V	Current supplied to load, A	MPPT rating
1.	1250	937.50	12	937.50/12 = 78.125 ≅ 78	12 V, 78 A

2.14 Fabrication of Thermoelectric cool chamber

The peltier (TEC) modules were installed with heatsink using thermal grease. A thermoelectric refrigeration system of 60 L capacity (outer dimensions: 690 x 400 x 440 mm) was fabricated with 50 mm thick thermocol and inside dimensions were 640 x 350 x 390 mm (thus total volume of 0.087 m^3). The main components of the developed thermoelectric cool chamber comprised insulated cooling chamber, peltier modules, heatsinks temperature and relative humidity sensor with data logger, DC power supply with controller, 300 Ah battery, solar charge controller and 4 SPV panels of 340 W, heat sink assembly- 12 V DC fan air cooled heat sink. The schematic diagram of the assembly of thermoelectric cool chamber is shown in Fig. 2.1. The developed thermoelectric cool chamber should attain cooling temperature in the range of 10 to 14°C and relative humidity of 70 to 80% when loaded with 40 L water at an ambient temperature in the range of 26 to 28°C. The developed thermoelectric cool chamber with fan air cooled heatsink is shown in Plate 2.1.

Plate 2.1 Developed thermoelectric cool chamber

III. RESULTS AND DISCUSSIONS

3.1 Performance evaluation of thermoelectric cool chamber with 40 L water

The performance evaluation of thermoelectric cool chamber with 40 L water was conducted. It was observed that, the chamber temperature in TCC unit was reduced from initial temperature by 8.47°C and 11.85°C after 12 and 24 hours respectively. Also, the water temperature in TCC unit was reduced from initial temperature by 8.12°C and 11.56°C respectively after 12 and 24 hours. The chamber and water temperature after 24 hours were reduced to 13.31°C and 13.49°C (Fig. 2.2) respectively.

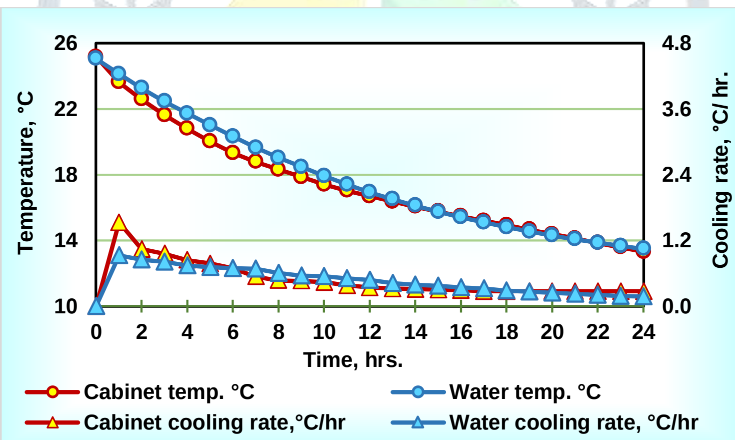

Fig. 2.2 Temperature and cooling rate of chamber air and water inside the TCC unit (40 L water)

It was observed that, by increasing water volume to 40 L, reduction in chamber temperature decreases. Thus, chamber air temperature was increased at same power and time duration due to increased heat that should be removed from cool chamber. The heat that could be absorbed by the thermoelectric was proportional to power supplied to it. Therefore, at higher heat the capability of peltier module (TEC) at the corresponding power was not enough to remove the heat. Consequently, the temperature inside the cool chamber increased.

Also, the water temperature decreased with time and water temperature also increased with increase in water volume. The heat transfer rate from water increased with increase in volume. When the peltier module was powered on, the cold side of peltier module (TEC) became cold as heat from air inside cool chamber flowed towards the cold side of TEC. Similar results were observed by Mirmanto *et al.*, (2018). It was reported that by increasing the water volume, cooler box space temperature was raised but decreased conduction heat transfer rate. While with no water volume, the conduction heat transfer rate increased and then remained constant. It was also reported that, at higher water volumes the COP decreased with the time. The effect of the water volume on the heat transfer rate of the air was negligible but it was significant on the total heat transfer and conduction heat transfer.

IV. CONCLUSIONS

The study highlighted that the cooling load and water volume inside the TCC unit had a significant impact on the cooling efficiency. By increasing water volume to 40 L, the chamber temperature decreased. Hence, chamber air temperature was increased at same duration of time and power. Similarly, the water temperature decreased with time and water temperature also increased with an increase in water volume. The heat transfer rate from water increased with an increase in volume. Larger cooling loads or increased water volumes led to reduced cooling efficiency due to limitations in the TEC's heat pumping capacity.

The study's findings are crucial for enhancing the design and operation of thermoelectric cooling systems. It was therefore concluded that for stand-alone solar photovoltaic systems the thermoelectric cool chamber with a fan cooled heat sink could be a more viable and cost-effective choice.

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