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A Mobile Tropical Cooling System Design Using a Thermoelectric Module

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ABSTRACT

The research conducted and described in this paper focuses on the design of a cooling system using thermoelectric or peltier module (TEM) and heatsinks with considerations for temperate climatic conditions. A case study of Nigeria has been chosen. Nigeria as a tropical region experiences high temperature difference between the year (18 - 40℃) with sunhours ranging between (100 – 210 hrs) monthly, such that the desire for chilled beverages almost throughout the day becomes paramount neccesitating the need for a peltier mobile cooler in tropical regions especially with inadequate electricity supply. A 9-litre rectangular shaped cooler was chosen with an area of 1.155m^2, a dimension of $0.65m \times 0.35m$, estimated to contain 120 beverages with an estimated heat load of 483W. It is estimated to use five thermoelectric modules, a temperature sensor, tec controller, DC powered battery and ten heat sinks. Comparatively, the design criterias of these peltier cooler were compared with the performance evaluation of existng similar designs and found to be within optimum performance levels. At 10℃, the thermoelectric modules are powered to start cooling until the beverages are at 0℃ (estimated to be a period of fifteen minutes), afterwhich the tec controller turns off power and the system is temporarily off until a temperature of 10℃ is detected by the temperature sensor and a re-cooling is initiated. With these the frozen beverage products received in the morning can be re-cooled as many times as possible.

1 Introduction and Background to Study

Refrigeration is the achievement of temperatures below that of the local environment, its always an artificial process, some adiabatic expansion of a fluid or other non-heat transfer process. Cooling on the otherhand refers to a process of transferring heat from an object in order to bring it to a lower temperature than ambient temperature. It's a heat transfer process that can be natural (left alone) or artificially accelerated by blowing, notwithstanding the words refrigeration and cooling are sometimes used indistinguishably even in scientific literatures. A conventional refrigeration system contains three fundamental parts- the evaporator, compressor and condenser, a peltier cooling system also has its analogous parts, a doped semi-conductor material which takes the place of the refrigerant, the condenser is replaced by a finned heat sink, and the compressor is replaced by a direct current power source. These fundamental differences give peltier cooler the following advantages; no moving parts, precise temperature control, no refrigerant, noise free operation, high reliability, light-weight and compact size,

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orientation-independence, longlife (exceeds 100,000 hrs) and quiet operating environment. The main drawbacks are highcost and low energy efficiency.

At the cold junction, energy (heat) is absorbed by electrons as they pass from a low energy level in the p-type semiconductor element, to a higher energy level in the n-type semiconductor element. The power supply provides the energy to move the electrons through the system. At the hot junction, energy is expelled to a heat sink as electrons move from a high energy level element (n-type) to a lower energy level element (p-type). [1]

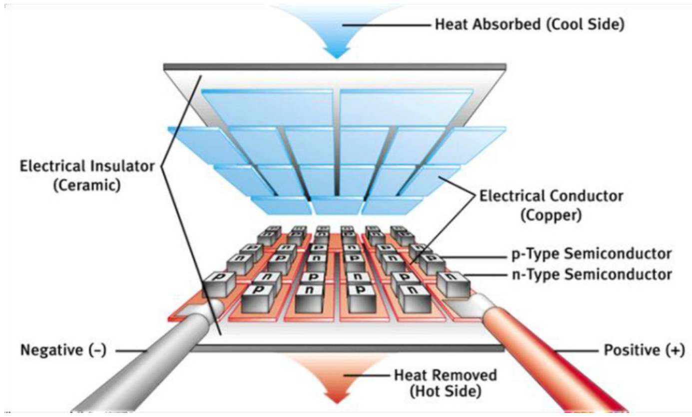


Figure 1: Overview of a peltier cooler module.

The first important discovery occurred when a German-Scientist, Thomas Seebeck, found that an electric current would flow continuously in a closed circuit made up of two dissimilar metals maintained at two different temperatures. A French watchmaker and part time physicist, Jean Peltier, while investigating the "Seebeck Effect" found an opposite phenomenon whereby thermal energy could be absorbed at one dissimilar metal junction and discharged at the other junction when an electric current flowed within the closed circuit. In the 1930's, the first radio to be powered by thermoelectrics was publicized, at that time also Russian scientists began studying some of the earlier thermoelectric work in an effort to construct power generators for use at remote locations throughout the country. This Russian interest in thermoelectricity eventually caught the attention of the rest of the world and inspired the development of practical thermoelectric modules using semiconductor technology in lieu of dissimilar metals. Later years commercial thermoelectric (peltier) cooler modules became available. [2][3]

A significant amount of research focused on the design and construction of peltier cooling system for varying applications such as picnic coolers, crash helmets, seat coolers, cooling vest, DNA synthesis, beverage and other product chillers etc. These designs were carried out based on varying selected parameters such as ambient temperature, amount of substance to be cooled, desired temperature of the cold product, power input etc, these parameters were mostly without proper considerations for tropical climatic conditions. Using Nigeria as case study, iced products are collected by vendors using well lagged beverage coolers from nearest franchise depot, these products are sold throughout the day along the distances covered by the vendors, it is observed that reduced sales as a result of dip in customer's sastification arises once the product temperature changes drastically. Existing challenges facing mobile beverage coolers are (i) inability of well lagged beverage cooler to retain iced (low temperature) products all through the day resulting in reduced sales (ii) vapour compression refrigeration system high reliance on electricity which is in inadequate supply (in Nigeria) (iii) global transition from fossil-fuel based energy to renewable energy (iv) harmful gas emission by chlorine and fluorine bearing refrigerants. With peltier mobile beverage cooling system designed with considerations for tropical climatic conditions the temperature of iced products received in the morning would be maintained throughout the day without any negative impact on the environment.

The general objective of this paper is to fully design a peltier mobile beverage cooler that can be used in maintaining frozen beverages for longer hours considering the tropical conditions like nigerian climatic. This research offers an alternative green cooling system with longer cooling capacity, having little or no maintenance cost, easy operation, uses renewable energy source, a system that can assure customers' satisfaction is maintained almost throughout the day and throughout different seasons of the year, and aimed at minimizing amount of tec modules to be used. Peltier Modules have come to dominate certain applications, and new benefits continue to emerge.

They are categorized as (i) medical Applications - potential avenue for wider use of thermoelectric devices lie in therapeutic medical applications such as temperature controllable blankets and couches. These devices are used for thermoregulations of cancer patients, other areas include cryotherapy, cryosurgery, ophthalmology, traumatology, neurosurgery, plastic surgery, gynaecology, urology, oncology, dermatology etc. (ii) electronics applications - tthermoelectric coolers can be used to cool computer components to keep temperatures within design limits without the noise of a fan, or to maintain stable functioning when overclocking. (iii) aerospace and telecommunication operations - applications include aircraft engine waste heat harvesting, high-efficiency cooling eliminating liquid cooling and associated thermal management weight, can be paired with solar cell to produce more power, while in telecoms can be used in digital transmission lasers, wavelength lockers, optical channel monitors, planar lightwave circuits, CATV transmission lasers, avalanche photodiodes etc. (iv) industrial Applications – thermoelectric cooling is used in computer microprocessors, robotics, dehumidifier, harsh emvironment protection of critical components and mini air conditioning. (v) domestic applications - thermoelectric devices are used for cooling small enclosures such as portable food / beverage containers, chilled water dispensers and wine cabinet. [4][5]

2 Literature Review

A great deal of research work, findings and efforts on thermoelectric materials, measures aimed at increasing the figure of merit of thermoelectric materials as well as some other thermoelectric design applications can be found in the literatures [6], [7], [8], [9], [10], [11], [12], [13], [14]. Performance evaluation of a thermoelectric refrigerator were conducted by [15] and [16] using matlab and finite difference method respectively, Francis [15] observed that at a temperature difference of 20°C, maximum cop was reached. The purpose of this research is to design a beverage cooler that could cool a product to its freezing point while minimising the amount of tec modules needed to achieve this by ensuring the beverages fed initially into the thermoelectric beverage cooler were not at ambient temperature but a maximum of 10°C. Subsequent re-cooling can be done as often as the product temperature reaches 10°C. An approach to the theoretical analysis of a thermoelectric beverage chiller was presented by [17], a beverage size of 474mL was cooled from ambient temperature (31°C) to 6°C using 6 tec modules and 12 heatsinks. Solar powered thermoelectric refrigeration system was presented by Manoj [19]; his experimental results shows a reduction of 11°C without any heat load and 9°C with 100ml of water within a period of 30 mins. Lertsatitthanakorn [20] designed, fabricated and evaluated the performance of a thermoelectric ceiling cooling panel composed of 36 TEMs with an indoor temperature of 27℃ and a cop of 0.82.

3 Design of Thermoelectric Beverage Cooler for Nigerian Climate

Nigeria like the rest of west africa is found in the tropics, where the climate is seasonally damp and very humid, with wide climatic variations in different regions of the country with temperatures ranging from 18℃ - 40℃ (as one moves from the middle belt – southern – northern regions in the country) between the rainy and dry season. Graphical illustrations of the climate of selected nigerian cities are stated below.

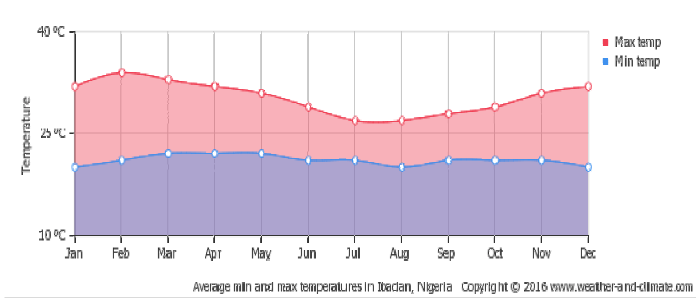


Figure 2: Average Temperature of Case Study Region

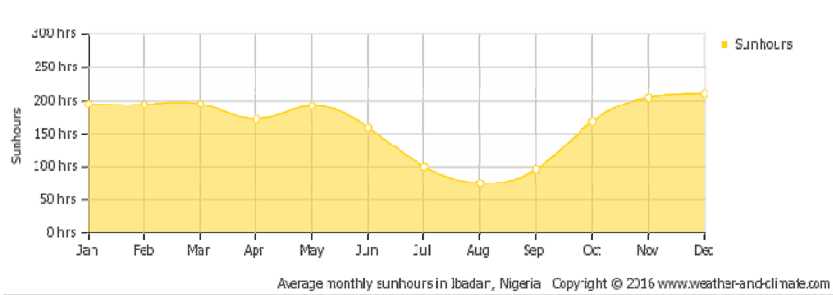


Figure.3: Average Monthly Sunhours of Case Study Region

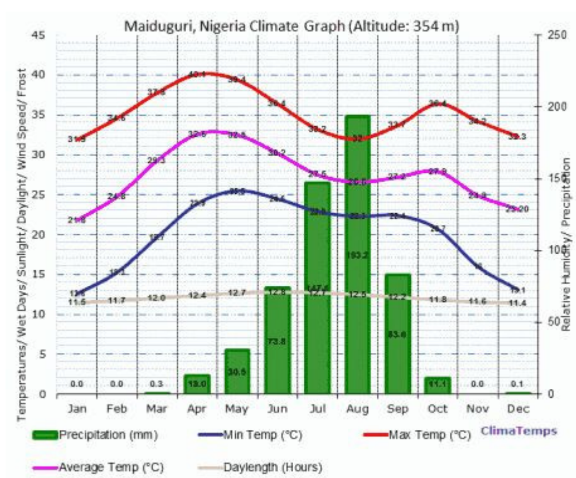


Figure 4: Climatic Graph of Maiduguri, Nigeria.

In order to design a thermoelectric mobile beverage cooler the following points must be considered. First is the geometry of the refrigerating chamber, next is the heat Load and lastly the material used.

3.1 Geometry

The geometry of the mobile cooler to be designed is rectangular, this is because it's easier to build and insulate unlike other shapes. It's detailed drawings are shown in Figure 5.

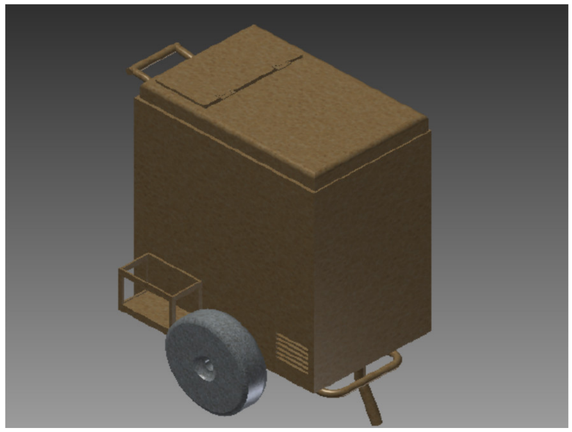


Figure 5: Thermoelectric Beverage Mobile Cooler Design.

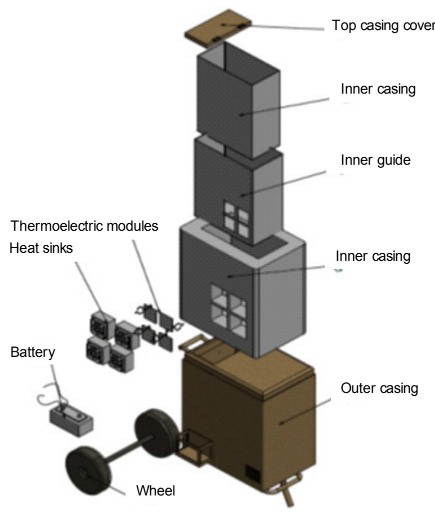


Figure 6: Exploded View

Table 1: Heat Load and Heat Transfer Method

S/N	Criteria	Symbol	Dimension	Design Value
1.	Weight of beverage	W_B	Kg	0.075
2.	Volume occupied by beverage	V_B	M^3	0.075
3.	Ambient Temperature	T_{amb}	℃	35
4.	Desired Beverage Temperature	T_B	℃	0
5.	Recommended temperature to initiate cooling	T_{cool}	℃	10
6.	Heat Sink Temperature	T_H	℃	45
7.	Time required for desired cooling	T_{req}	S	900
8.	Heat load supplied by beverage	$Q_{beverage}$	W	500
9.	Thermal resistance of Heat Sink	R_H	K/W	0.04

10.	Specific heat capacity of beverage	C_P	J/kg.k	4186
11.	Thermal conductivity of Aluminium	K_{Al}	W/m.k	167
12.	Thermal conductivity of Syrofoam	K_{syro}	W/m.k	0.033
13.	Beverage size	B_s	M	$0.15 \times 0.5 \times 0.5$
14.	Cold Compartment size	C_c	M	$0.65 \times 0.35 \times 0.35$
15.	Amount of beverage to be cooled	A_B	-	120
16.	Heat load absorbed by a TEM	Q_{TEC}	W	100

3.1.1 Product Load

Volume of Beverage to be cooled is (V_B*A_B) ml = 0.075 × 120 = **9** litres ; Mass of Beverage to be cooled is $(9 \times 10^{-3}) m^3 \times (1000\,) kg\,/\,m^3$ = **9** kg. Using Newton's law of cooling eq.(1) & (2) are used to find product load.

$$Q = M\, C_p\, \Delta T \tag{1}$$

and

$$Q_b = \frac{M\, C_p\, \Delta T}{T_{req}} \tag{2}$$

3.1.2 Thermal Load

Combined Heat transfer through the walls of an insulated enclosure is given by eq. (3)

$$Q_T = \frac{A\ \Delta T}{\frac{1}{H} + \frac{X}{K}} \tag{3}$$

Where A = area of enclosure, ΔT = Amb. Temp – Cold side Temp, H= convective heat transfer coefficient, x = thickness of insulation, k = thermal conductivity of insulation. Heat Transfer by Radiation is given by eq. (4)

$$Q_{RAD} = F\,\epsilon\,\sigma\,A\,(T_H{}^4 - T_C{}^4) \tag{4}$$

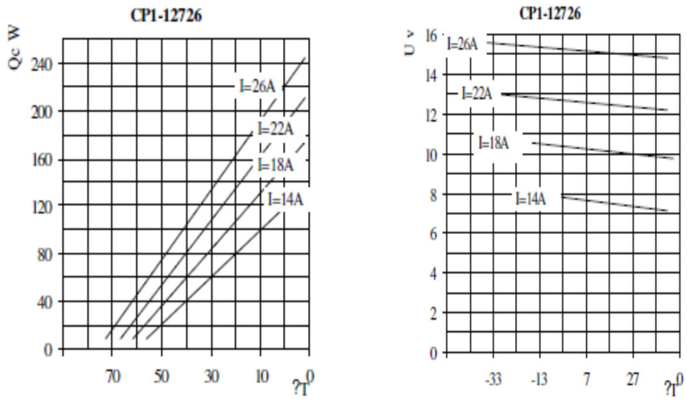
Total Heat load = Product Load + Heat Transfer Loads is given by eq.(5)

$$Q_{beverage} = (\ Q_b + Q_T + Q_{RAD} \tag{5}$$

Q_{TEC} is determined by graph (A). Thermal Resistance of Heat Sink is given by eq.(6)

Table 2: TEC module parameters

Type	Imax (A)	Vmax(V)	Qc max(w) ΔT = 0	ΔTmax (°C)	Couples	R (Ω)
CP1-12726	26	15.4	243.5	68	127	0.04



Graph A Graph B

Figure 7: TEC module performance graphs

$$R_H = \frac{T_H - T_{amb}}{VI + Q_{tec}} \quad (6)$$

Keeping heat sink 10°C above ambient temperature, $T_H = T_{amb} + 10°C$. A heat sink rating of 0.04K / W or less must be used with each TEC module. Heat produced internally by each TEC Module. IV or I^2R = 10 * 18 = 180 Watts (as shown by graph B). Cold Compartment Dimensions are: Top and bottom panel dimensions = $0.35 \times 0.35\ m$; Vertical sides panel dimensions = $0.65 \times 0.35m$; Front and back panel dimensions = $0.65 \times 0.35m$; Area of vertical side cold compartment = $0.65 \times 0.35 \times 2 = 0.455m^2$; Area of top and bottom compartment = $0.35 \times 0.35 \times 2 = 0.245m^2$; Area of front and back compartment = $0.65 \times 0.35 \times 2 = 0.455\ m^2$; Total Area = $0.455 + 0.455 + 0.245 = 1.155\ m^2$; Size Of Battery Needed is given by Eq. (7). A battery of 250 Ah is recommended to avoid over draining the battery bank.

$$T_{W_H} = T_{D_C} \times T_H \quad (7)$$

$$T_{A_H} = T_{W_H} / V = \frac{1500}{12} = 125\ \text{Amp} - \text{hr}$$

3.2 Materials Needed For Thermoelectric Beverage Cooler

Table 3: The Part list for the construction of a thermoelectric beverage cooler

S/N	QTY	PART	DESCRIPTION
1	1	Top Cover	Made up of three layers; aluminium sheet, syrofoam and mild steel (outer layer)
2	1	Inner Casing / Cold Compartment	Aluminium sheet with (five) tec module dimensions cut out
3	1	Inner Guide	Aluminium sheet to prevent direct contact between beverage and TEM
4	1	Insulation	Usually Syrofoam joined together by adhesives
5	1	Outer Casing	Mild steel sheet for protection against harsh environmental conditions.
6	5	Thermoelectric Modules	12V, 26A
7	10	Heat Sink	Two for each TEM
8	2	Tyres	Good rubber tyres
9	1	Battery	12V, 30A
10	1	Battery Housing	10% higher than battery dimensions

11	1 tube each	Thermal Grease	module – heat sink, inner guide – inner casing, top cover, syrofoam etc.
12.	Varying sizes	Screws	To hold module-heat sink assembly tightly and other items.
13.	Varying sizes	Wires	Modules, Heatsinks, sensor, battery
14.	2	Hinges	To join the top cover and outer casing
15.	1	Temperature Sensor	To measure precise product temperature
16.	1	Circuit Board	For controlled circuit electronic arrangement
17.		Metal Rod	For support when stationary(base rod) and for push and control during motion (handle).
18.	1	TEC controller	For enhanced long-term reliability of the system.

Figure 8: sample of beverage to be cooled.

3.3 Production Status Of Thermoelectric Beverage Cooler Materials

The ease of purchase of major componenets which makes up the mobile beverage cooler is considered by determining their production status in Nigeria where applicable for faster product development and ease of foreign exchange.

S/N	PART NAME	PRODUCTION STATUS	REMARKS
1.	Temperature Sensor	Produced Locally	Readily available in the market.
2.	Thermoelectric Modules	Not manufactured currently in Nigeria. Nanotechnology advances & applications are still in limited scope.	Can be easily ordered for online.
3.	Heat Sink	Not manufactured currently in Nigeria.	Readily available in the market
4.	Syrofoam	Produced locally	Readily available in the market
5.	Thermal Grease	Good Quality thermal grease are presently not manufactured in Nigeria.	Readily available in the market
6.	Aluminium Sheet	Produced locally	Readily available in the market
7.	Battery (D.C Power)	No local production yet.	Readily available in the market
8.	Other accessories (wires, screws, hinges, circuit board, hand tools etc.)	Produced locally	Readily available in the market

4 Performance Evaluation

4.1 The Strengths of Peltier Systems

In general, Peltier elements are very reliable, low maintenance and durable due to the absence of moving parts subject to wear. In addition, they operate quietly and vibration-free. They can be small and lightweight even when combining several modules in one element. Another advantage is low-cost manufacturing. Peltier systems contain no refrigerants that are flammable, ozone depleting or that contribute to the greenhouse effect. The entire cooling system with compressor, inductor and large evaporator and condenser components is eliminated. Peltier elements are maintenance-free, quick and easy to replace in case of failure. State-of-the-art control technology makes it possible to more accurately meter the cooling effect than for conventional compressors. It is also possible to reverse the function of the system by reversing the polarity, i.e. a cooling element can be turned into an efficient heating element.

4.2 The Weaknesses of Peltier Systems

With Peltier modules, there is no way technically to get around that fact that the hot and cold sides are very close together. In practice, today‘s Peltier modules are only 3 to 5 mm thick. This fact makes it particularly important to efficiently carry the heat to and from the module. Technically, this is handled by large heat sinks with fans. The performance of a Peltier module is directly related to the required temperature difference. The greater this difference in temperature, the lower the pumping capacity until it (based on the present state of Peltier technology) comes to a complete standstill at approx. 70 K. Greater temperature differences can only be accomplished by complex multistage elements.

4.3 The Energy Efficiency

Peltier elements can absorb heat on one side and dissipate heat on the other. The medium used for this reversible pumping process is the electric current or its charge carriers. The current acts to some extent as refrigerant in the cooling cycle and the pumping capacity is proportional to the current flow. It is unpreventable that this current is irreversibly converted into Joulean heat in the Peltier element. The generation of heat not only means a loss of power, but in addition, the resulting loss of heat on the cold side must be compensated for by the pumping capacity before a net cooling capacity results. In practice, a multiple of heat pumping capacity must be accepted as loss of power for Peltier systems. [20]

4.4 Performance Evaluation Graph For Thermoelectric Beverage Cooler

Figure 9 shows that the COP increases with increasing current up to a certain value before further decreasing, i.e. there exist an optimum current at a particular high voltage when all other parameters has been kept constant. From figure 10 it can be observed that as the temperature difference (Th-Tc) increases, the COP of the system decreases. This is due to the fact that more work has to be supplied in the form of electrical power which results in more heat losses due to Joule Effect.

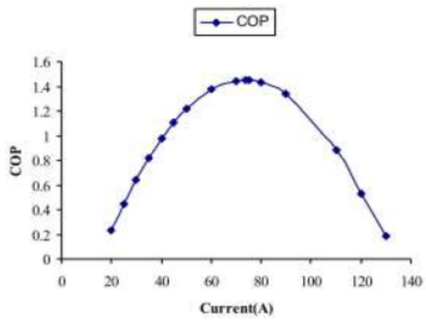


Figure 9: Variation of COP with current

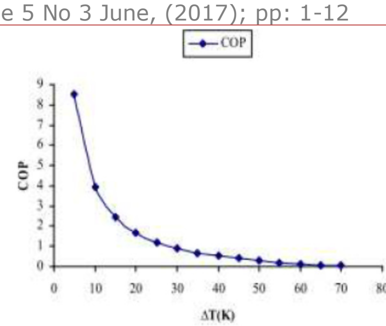


Figure 10: Variation of COP with Temperature Difference

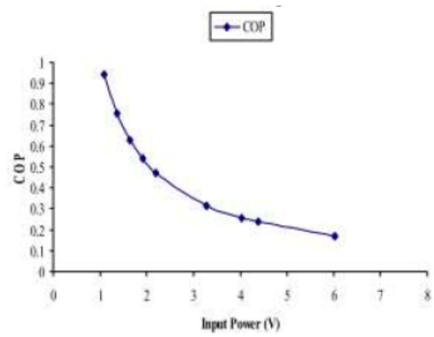


Figure 11: Variation of COP with input power

From figure 11 it can be observed that the COP decreases with increase in input power. This happens due to increase in voltage, the current increases as well (Power = IV) hence more heat is being transferred at the hot end that results in lowering the cold end temperature. [21][22]

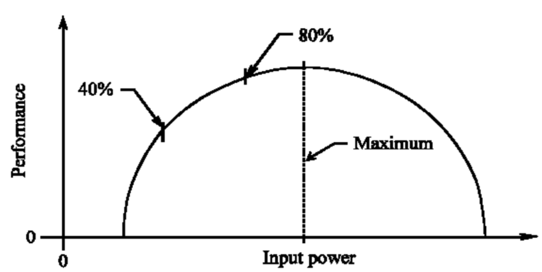


Figure 12: Variation of performance with input power for a TEC Module.

The performance of the thermoelectric module (CP1-12726) can also be evaluated graphically by using the performance evaluation graphs above. At a temperature difference of 20℃ ($\Delta T_{max} = 68℃$) and current of 18A ($\mathrm{I_{max}} = 26\mathrm{A}$) and input power of 180 watts (I = 18A, V= 10 volts), it can be assessed that the temperature difference and current falls within the optimal level of the graph.

5 Conclusion and Recommendation

Peltier technology opens new opportunities for special applications, its scalability and location independence enable the development of small or portable units. Peltier modules make temperature control efficient at lower temperature gradients by fine metering of cooling capacity. Despite these, peltier coolers have dominated other areas where vapour compression system seems ineffective such as crash helmet cooling (in middle east / asia), fire fighter vest, mobile peltier cooler, blood tissue storage, DNA synthesis, cooling of electronic components, seat coolers etc. It's expected that the peltier beverage cooler designed would use five thermoelectric modules, each absorbing a heat load of 100 watts and ten heatsinks, one for each side of the five modules, such that within an estimated time of 15minutes a beverage size of 9litre can experience a temperature reduction of 10°C, ensuring that customers' can get frozen product almost throughout the day and different seasons of the year.

And with nanotechnology or nanothermoelectric materials the figure of merit of thermoelectric materials is expected to further increase leading to further efficient and higher heat absorbing modules, emergence of new applications and reduction in manufacturing costs.

The following however has to be observed to make the mobile cooler highly efficient, the battery housing must be moisture proof, also the module – heat sink assembly must be joined properly as well as the vent must be made free from particles or objects that could minimise convective heat transfer. Others include proper electrical wiring of the mobile cooler, recharging of the d.c powered battery after each day's use, corrosion of the outer casing must be avoided.

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