An Experimental Design and Analysis of Portable USB Powered Thermo Electric Cooler

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Abstract— Refrigerators are energy consuming home appliances and for this reason researchers are performed to enhance performance work of the refrigeration systems. Most of research work done so far deals with an objective of low energy consumption and refrigeration enchantment. Thermoelectric refrigeration is one of the method to produce refrigeration effect. This project demonstrates how far thermoelectric refrigeration can be modified to produce refrigeration effect with low power input and high cooling effect. In this project a portable thermoelectric (Peltier) cooler is designed and fabricated for multipurpose use (Like beverage cooling, water cooling, and milk storage). It is operated on USB with low power, it is portable in nature, compact in seize. This project carries out cooling effect analysis, FEA steady state heat transfer analysis in ANSYS software on PET water bottle material with heat transfer plates, thermal insulation jacket. Power consumption of TEC device is experimented and calculated with practical model on DC-DC boost converter.

Keywords: Peltier Module, USB, DC-DC Boost Converter, Heat Transfer Plates, Thermal insulation Jacket, FEA Steady State Heat Tansfer Analysis

I. Introduction

Conventional refrigerators consist of huge moving parts like compressor, pump and condenser which consume a lot of energy. The invention and use of non-conventional alternatives has been effective to a great extent due to the numerous researches employed towards the design and development of green energy sources. Thermoelectric coolers works on the Peltier effect which also know by the more general name thermoelectric effect. TEC module consists of two sides, when a DC current flows through the module, it brings heat from one side to the other, so that one side gets cooler while the other gets hotter. Heat sink is attached to the hotter side so that it remains above the ambient temperature, while the cool side goes below thambient temperature. In some other applications, multiple cooling sytems can be used together for lower temperature.

The main advantages of a TEC compared to a vapor-compression refrigeration system are it is lack of moving parts for circulating liquid, very long life, insusceptible to leaks, small size, and flexible shape. It also takes less time to develop more cooling effect in small considered area, desired set point temperature control obtained on variation of DC voltage with low power consumption. This factor reflects thermoelectric coolers are most preferable device in portable refrigeration domain.

II. Problem Statement

In portable thermoelectric coolers for effective cooling it required good heat sink design for large heat dissipation, high current flow across its P-N junction couples and easy to portable body structure, optimized C.O.P. Due to this reasons portable thermoelectric refrigerators in small seize (in use) are still lack in market.

III. Solution for the Problem

In this project an effective heat sink with its proper cooling system in compact seize is designed and experimented. A DC to DC current series step up circuit for boosting high current with low voltage for TE module will be developed, electronic power monitoring system for axial cooling fan speed control to be fabricated. Also thermal insulation jacket with aluminum heat transfer plates will be prepared to insulate and increase effective cooling of PET water bottles which mostly used in regular daily life.

IV. Scope of Research

This device widely used in commercial applications like beverage cooling, water bottle cooling, milk storage and medicine storage while travelling or in office use, domestic use where space and energy matters a lot.

V. Research Methodology

This experiment is carried out in following three stages:

1) Stage 1: Preparation of Peltier module and heat sink, its cooling system CAD model.
2) Stage 2: Design and test electronic power monitoring circuit for heat sink cooling operation at different axial fan RPM basing on heat sink practical prototype temperature.
3) Stage 3: Prepare TEC CAD and practical model, thermal insulation jacket; perform FEA steady state heat analysis on PET water bottle optimise cooling performance, design and fabricate DC boost converter circuit and test it with TEC.

A. Design of Peltier Module:

Peltier module (TEC01-12715) as shown in Fig. 1 complete seize is (40×40×4)mm, Flatness/parallelism is 0.05mm.

Fig. 1: Bi_2Te_3 TE Module of 127 thermocouples.

In this all TE elements are assembled in series by soldering (T100: BiSn (Melting Point=138ºC)) from analysis known that each TE couple maximum resistance is about 9.4489 milliohms (Total No. TE couples: 127) so total TE module resistance (9.4489×127=12 Ω) in same manner each couple takes optimum voltage of 10mV, Total TE module optimum voltage (10×127=12.7V).

1) TEC Governing Equations:

$$Q = (\alpha_p - \alpha_n) T_1 I - U (T_2 - T_1) - ½ I^2 R \quad [1]$$

Where Q is heat rejection in watts and $(\alpha_p - \alpha_n)$ is the mean thermoelectric power or Seebeck coefficient in the temperature range T_1 to T_2 , U is the effective thermal conductance between the cold and hot junctions, and R is the total electrical resistance of TEC (conductors + contact resistance at junctions). Power input (W) by the battery must attain for the power loss of the Joulean Effect and counteract the generation of power by the Seebeck Effect. Thus,

$$W = (\alpha_p - \alpha_n) (T_2 – T_1) I + I^2 R \quad [2]$$

The Coefficient of Performance of the system as a refrigerating device is defined as

$$C.O.P. = Q / W \quad [3]$$

Observations	
P Type material Seebeck coefficient (α_1)	$5×10^{-4}$ V/K
N Type material Seebeck coefficient (α_2)	$-7.2 ×10^{-5}$ V/K
Thermal Conductivity (k)	1.5 W/ K
Effective Thermal Conductance (U)	0.06 W/ K
Resistivity (ρ)	$1×10^{-5}$ Ωm
Figure of merit (Z)	$2.67×10^{-3}$

Table 1: Bi_2Te_3 material based Peltier module practical parameters observations at 21^0C.

B. *Heat Sink CAD Model:*

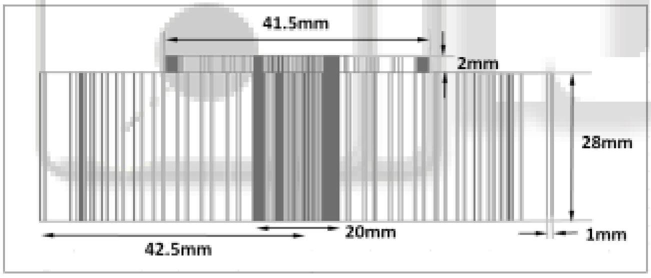

Fig. 2: Heat sink sectional and side view.

Fig.3 shows the CAD model of the heat sink which made of aluminum 6063 alloy and it consists of equally spaced radial fins attached to the central cylindrical core with 11^0 spacing. In application, the heat sink under study is mounted over the Peltier module for easy dissipation of the heat, and heat sink is cooled by forced convection heat transfer mode. In this axial curved cooling fan is used for creating forced air pressure and velocity within heat sink fins circular array enclosure to create heat transfer between fluid and solid bodies.

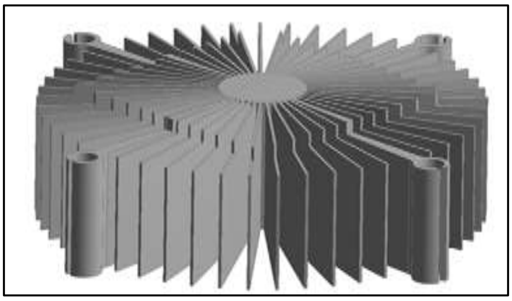

Fig. 3: Heat sink 3D isometric view.

C. *Cooling System for Heat Sink:*

Hence their name, this fans blow air along the axis of the fan. The more use of axial flow fans (Fig. 5) for fluid movement and heat transfer problems has resulted in detailed research into the performance attributes of many designs. The numerical study was performed to quantify the operation of axial fan and their flow characteristics. This fan consist of brushless DC hub motor which operates on 12V DC with PWM signal by which speed is controlled.

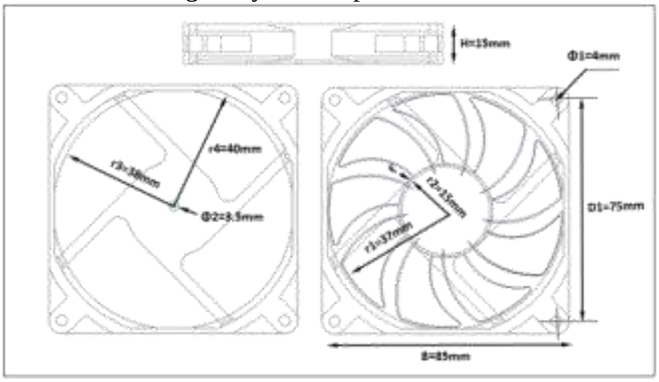

Fig. 4: Dimensional sketch of axial fan.

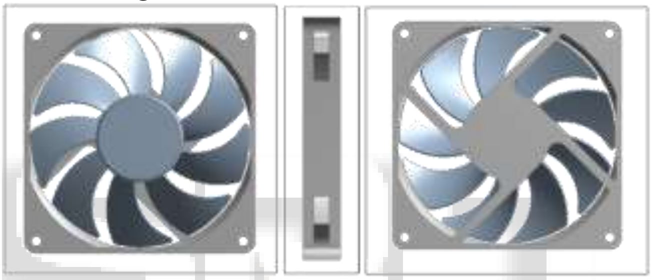

Fig. 5: 3D CAD model of axial cooling fan.

SI. No.	RPM	Rated voltage (V)	Rated current (A)	Flow rate ft^3/min (CFM)	Noise (dBA)
1	2800	12	0.10	21.10	27.0
2	3300	12	0.12	25.70	31.0
3	3800	12	0.17	29.60	35.0
4	4300	12	0.25	33.50	39.0

Table 2: Axial curved cooling fan practical observations

D. *Electronic Power Monitoring System:*

It is used to avoid continuous run of fan. Also it increases system efficiency and decreases power consumption, reduces fan noise while running. This system maintains efficient cooling of heat sink depending upon rise of temperature. This task is mainly done with temperature sensing module and open microcontroller based hardware which in terms understands the output temperature and controls PWM (Pulse width modulation) signal of axial fan. So that RPM of fan is varied due to this air flow rate is controlled.

The main components of this circuit is following:

– Arduino UNO R3 open source programmable hardware.
– NTC Thermistor temperature sensor.

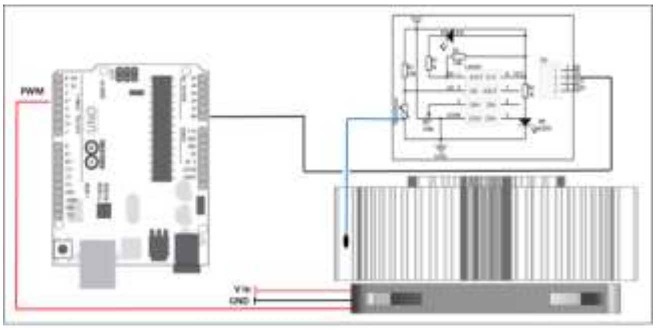

Fig. 6: Power monitoring system circuit diagram.

1) Code for Axial Fan PWM Signal Control:

```
int sensorPin = A0; // Input analog signal from NTC module
int PWM = 3; // Output PWM signal to fan
int sensorVal;
int PWMVal;
void setup() {
pinMode(sensorPin, INPUT);
pinMode(PWM, OUTPUT);
// baud rate setting
Serial.begin(9600);
}
void loop() {
// this code prints sensor value to the console.
Serial.println(sensorVal);
delay(1000);
// read sensor value and setting upper limit.
sensorVal = analogRead(sensorPin);
if(sensorVal >800){
sensorVal = 800;
}
// mapping and assigning the PWM values to the fan output
0 to 255 corresponds   to 0 to 100%.
PWMVal = map(sensorVal  150,  250, 350, 450, 800);
// 450 is output cutout or cut in limit where the fan turns off
to the lower PWM limit.
if(sensorVal <450){
PWMVal = 0;
}
// writing the PWM value to the PWM output pin.
analogWrite(PWM, PWMVal)
}
```

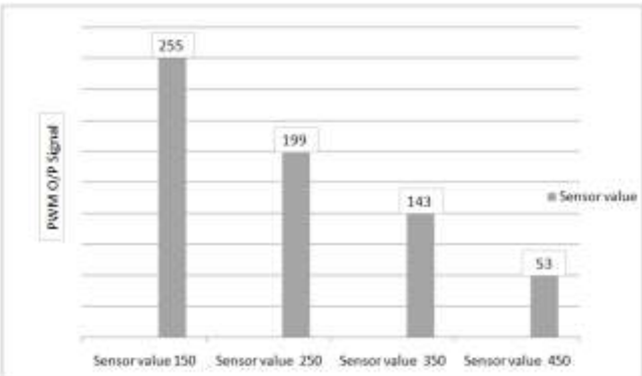

Fig. 7: Graph of sensor value vs. PWM O/P signal.

Above graph explains how PWM output signal is varied basing on sensor input signal.

RPM	PWM Voltage(mV)	PWM value	PWM %
2800	1090	53	17
3300	2180	143	35
4300	4360	199	71
4800	5060	255	100

Table 3: PWM output parameters.

E. DC-DC Series Boost Step-up Module:

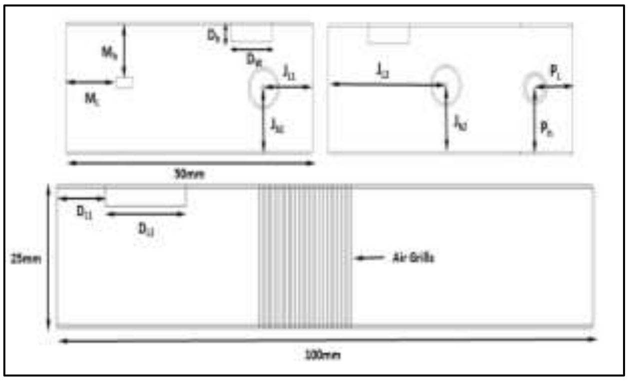

Fig. 8: 2D view of DC-DC series booster.

DC-DC series boost step-up module helps in stepping-up voltage, current for Peltier optimum performance at portable use. This module consists of three namely circuits as follows:

– XL6009 DC-DC booster/Inverter.
– TS4056 Mini USB series connector.
– S-8254A Battery management system.

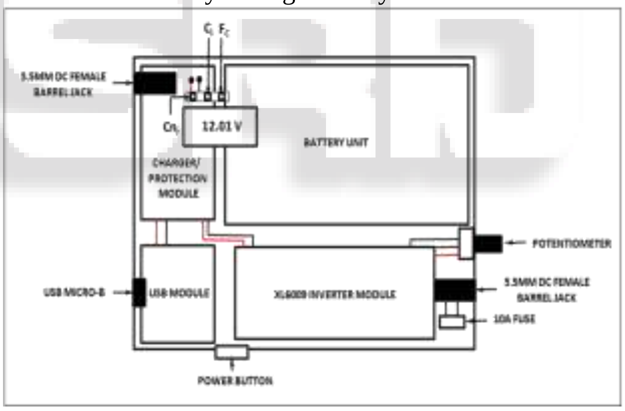

Fig. 9: Block diagram of DC-DC series booster.

As shown in above Fig. 8 DC-DC series booster of seize (100mm×50mm×25mm) consists of Front DC female barrel jack of (5.5mm) for charging 1850 batteries this jack is placed at length J_{L1} = 10mm and height J_{h1} = 10mm. As per front DC barrel jack another DC female jack was placed on body back side at length J_{L2} = 24mm and height J_{h2} = 9.5mm, Potentiometer is placed at length P_L = 15mm and height P_h = 9.5mm for step-up output power supply control, micro USB for extra power input is placed at length M_L= 10mm and height M_h = 8.3mm. Also power indicating LCD display with series indication LED's are placed at length D_{L1} = 8.9mm, D_{L2} = 15mm and width of display is D_W = 8.3mm, height of display D_h = 5mm. Fig. 9 shows complete block diagram of DC-DC series booster in which C_i indicates charging, F_c indicates Float charge, Cn_i indicates connectivity with micro USB. In this 10A fuse was also provided for safety purpose in case of short circuit in series to the DC output.

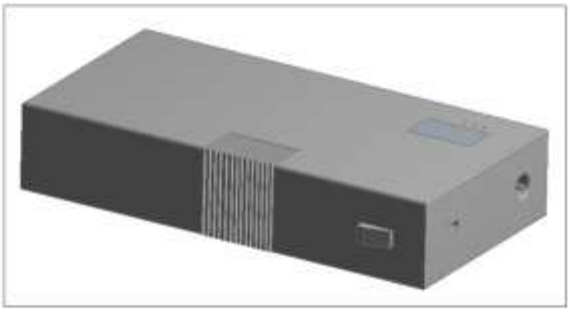

Fig. 10: 3D CAD model of DC-DC series booster/inverter device.

Input voltage	Power dissapation (PD)	Max. output voltage/current
3S batteries (3.7V×3=11.1V).	100mW/h	12.7V/3.2A
USB output(4.0V) + battery 3S(11.1V)=15.1V	140mW/h	12.9V/4.0A

Table 4: DC- DC series booster/inverter power parameters.

Note: USB input voltage should not cross 5V, Max. input charger volatage/current is 19.3V/3.3A.

As shown in below graph (Fig. 11) output voltage/current variation done with the help of potentiometer. This parameter controls Peltier contact cooling rate (low, medium, and high) basing on consumer temperature requirement.

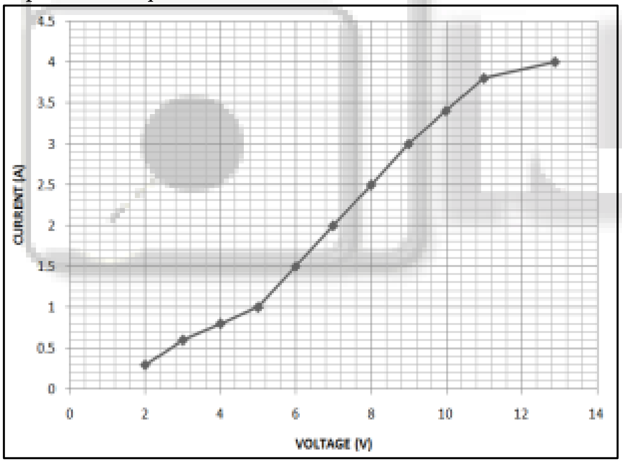

Fig. 11: Graph of output voltage vs. current of DC-DC series booster.

F. *Final TEC Device Design:*

Fig. 13 shows complete design of thermoelectric cooler with bottle cushion and support stand attached to heat sink with inbuilt Peltier.

Fig. 13: TEC complete design.

G. *Thermal Insulation Jacket with H.T Plates:*

In this TEC thermal jacket is used to hold bottle inside temperature for more duration, also it resists the contact of cooling area with outer environment(Outside temp.). In this paper steady state heat transfer of PET water bottle is analysed with thermal jacket and HT plates in ANSYS software to study how far heat is rejected from the body.

1) Geometry Details Thermal Jacket with H.T Plates:

As shown in below Fig. 14 thermal jacket (Height of jacket I_h = 160 mm) with heat transfer plates are designed in ANSYS workbench (Design modeler). This jacket consists of two layers namely:

1) Non woven fabric of thickness I_{t1} = 1.5 mm.
2) PVC film thickness on fabric of I_{t2} = 1 mm.

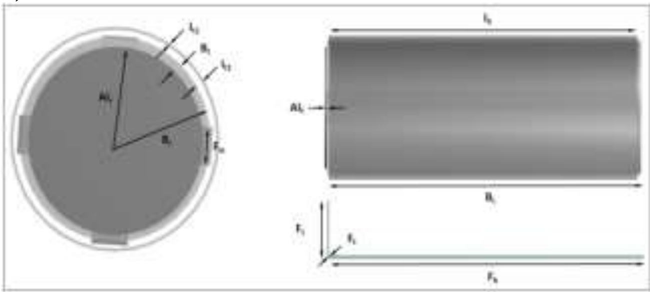

Fig. 14: Dimensions of water PET bottle with H.T plates and thermal jacket.

It also consists of L-shaped heat transfer plates of thickness F_t = 1mm, height F_h = 160mm, Length F_L = 25mm, F_W is the width of plate 20mm (used for heat absorption). B_t is the thickness of bottle 1.5mm, B_L is the length of the bottle 160mm, B_r is the radius of bottle 30mm Al_r is the radius of aluminum plate 28mm, Al_t is the thickness of aluminum plate 1mm. In below Fig 15 a) shows Thermal insulation jacket with fixed heat transfer plates, b) Shows heat transfer plates around bottle, c) Complete cooling load set up which is placed above on TEC.

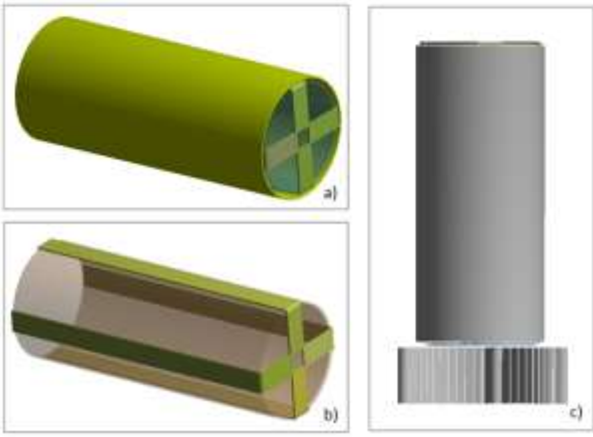

Fig. 15: 3D model of TEC with Al H.T plates and thermal jacket.

2) Materials used for Simulation

In this research PET(Polyethylene terephthalate) material is used which is common material for domastic water bottles manufacturing. Copper alloy, and aluminum alloy is used for simulation of heat transfer plates in thermal jackets for testing heat rejection rate and observe cooling performance of bottle. As shown in below table aluminum alloy, copper alloy, PET plastic material, PVC(plasticizer, flexible) filmed on non woven fabric material, air and water properties are tabulated.

Material Names	Density (kg/mm3)	Viscosity (Mpa/s)	Isontropic thermal conductivity (W/mm.^{0}C)
Al	2.77e-06	-	1.8e-1
Cu	8.3e-06	-	0.401
PET	1.34e-06	-	0.000144
PVC	1.33e-06	-	0.000179
Air	1.225e-09	1.7894e-11	2.42e-05
Water	9.982	1.003e-09	0.0006

Table 5: Material Properties.

3) Meshing:

APDL (ANSYS Parametric Design Language) solver is used to mesh TEC model of four node three dimensional square element (5 mm element seize) as shown in Fig. 16. Meshed model bounding box diagonal is 231.7 mm, average surface area is 981.19 mm^2, No. nodes is 99614 and No. elements are 19501.

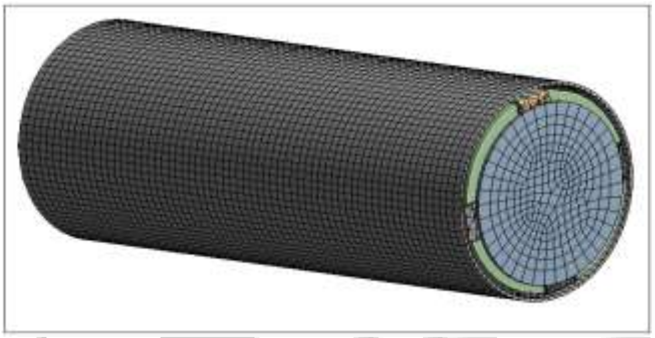

Fig. 16: Meshing H.T plates and thermal jacket with PET water bottle.

4) Boundary Conditions Loading:

In this two boundary conditions are loaded for simulation, one is for bottom circular TEC aluminum plate (cooling temperature) of -2^{0}C, Second boundary condition is for bottle outer area convection film coefficient (22^{0}C, 5e-006 W/mm^2.^{0}C) as shown in below Fig. 17.

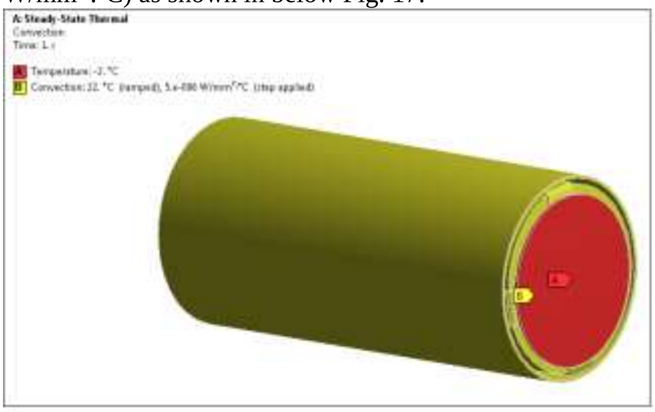

Fig. 17: Boundary conditions of water bottle with H.T plates and thermal jacket.

5) Solution:

In this solution is divided into following simulations:

a) PET Water Bottle without H.T Plates:

In Fig. 17 temperature and heat flux distribution on PET water bottle without heat transfer plates was shown, in this water bottle is supposed to test under -8.4192^{0}C temperature on TEC cooling plate in ANSYS steady state heat transfer mode. So, in this it observed that in PET water bottle without H.T plate's heat rejection rate is very low, more than half of bottles inner water remains at 21.969^{0}C as shown in below simulation.

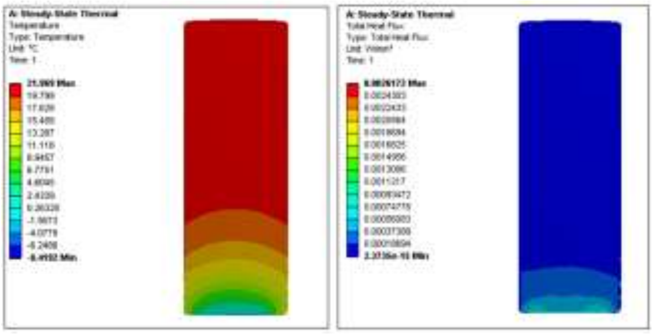

Fig. 17: PET bottle temperature and heat flux simulation (without H.T plates).

b) PET Water Bottle with H.T Plates:

In this simulation PET water bottle is tested with thermal jacket and heat transfer plates. For better heat rejection we used two different high thermal conductive, corrosion free materials i.e Aluminum and copper.

c) Alunimun H.T plates:

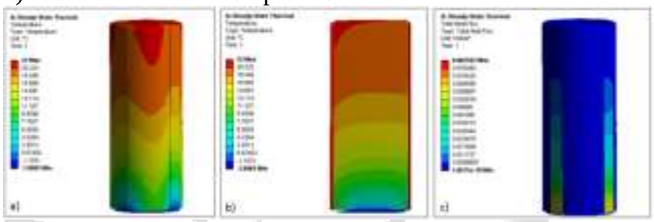

Fig. 18: PET bottle temperature and heat flux simulation with Al H.T plates.

In this PET water bottle is tested under Aluminum H.T plates which fixed in thermal insulation. Plates max. temperature observed 220C, Min.: -2.8803 0C, average: 14.8910C and heat flux distribution observed max.: 8.2162e-002 W/mm², min.: 1.0571e-019 W/mm², average : 1.5275e-003 W/mm² as shown in above Fig. 18.

d) Copper H.T plates:

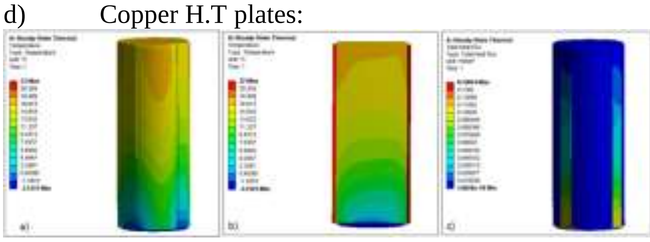

Fig. 19: PET bottle temperature and heat flux simulation with Cu H.T plates.

As shown in Fig. 19 PET water bottle is tested under cupper H.T plates which fixed in thermal insulation plates Max temperature observed 220C, Min.: -3.1375 0C, average: 13.198 0C and heat flux distribution observed Max.: 0.14054 W/mm², Min.: 1.0026e-019 W/mm², average : 2.9738e-003 W/mm².

Below figure shows complete practical tested model in different views with water bottle which is covered of thermal insulation jacket.

Fig. 20: Final practical working model.

VI. PRACTICAL OBSERVATIONS &CALCULATIONS

In this TEC ideal testing on DC to DC boost converter with themal jacket and H.T plates. Below shown (table no. 6) details performance data.

Time (min)	Cold side temp(^{0}C)	Hot side temp(^{0}C)	ΔT(^{0}C)	Current(A)
1	29.3	34.4	5.1	3.44
2	26.7	38.9	12.2	3.37
3	24.1	41.5	17.4	3.35
4	21.5	41.7	20.5	3.34
5	18.1	41.8	23.7	3.34
6	16.2	42.2	26	3.35
7	13.4	42.5	28.6	3.35
8	10.9	42.0	31.1	3.35
9	8.2	42.0	33.8	3.35
10	5.0	42.0	37.0	3.35

Table 6: TEC practical test observations.

Note: In this test voltage is constant (12.7V).

A. Practical Test Calculations (from observations):

Peltier Dimensions = (40x40x4) mm
Mass = 25gms
Density = 7.642g/cm^2
Current = 3.35 A
Current Density, J = 625A/m^2
Voltage = 12.7 V
Resistance = 3.6 Ω
Temperature of Hot Side (T1) = 42^{0}C
Ambient Temperature = 32^{0}C
Convective Heat Transfer Coefficient (Forced Convection - Air) = 137.5 W/m^{2}K
Specific Heat Capacity of Air = 1.1 J/g ^{0}C
From experimental data,
T2 = $T_{\text{Cold side}}$= 5 ^{0}C
Temperature Difference, ΔT=37^{0}C
From equation(1),(2)&(3)

$Q_1 = (\alpha_1 - \alpha_2)\, T_1 I - U\,(T_1 - T_2) - \frac{1}{2} I^2 R$
$= (5\times 10^{-4} + 7.2\times 10^{-5})315\times3.35 - 0.06(37) - \frac{1}{2}\times3.35^2\times3.6$
$= 21.81W$

$W = (\alpha_1 - \alpha_2)\,(T_1 - T_2)\, I + I^2R$
$= (5\times 10^{-4} + 7.2\times10^{-5})\,(37)\,3.35 + 3.35^2\times3.6$
$= 40.47\ W$

C.O.P = Q1 / W
= 21.81/40.47
= 0.53

1) *Load Calculations:*
1) Active Heat Load:
$Q_{active} = V^2/R = VI = I^2R$
$= 12.3^2/3.6 = 42.025\ W$
2) Radiation:
$Q_{rad} = F\ e\ s\ A\ (Tamb^4 - T_c^4)$
$= 1\times1\times5.667\times10^{-8}\times2.1\times10^{-3}(305^4 - 278^4)$
$= 0.319W$
3) Convection:
$Q_{conv} = h\ A\ (Tair - Tc)$
$= 137.5(2.1\times10^{-3})\ (305-278)$
$= 7.796W$
4) Conduction:
$Q_{cond} = (k\ A)\ (\Delta T)/\ (L)$
$= 1.5(2.1\times10^{-3})(37)/(0.04)$
$= 2.913W$
5) Total Load:
$Q_{Total} = Q_{active} + Q_{rad} + Q_{conv} + Q_{cond}$
$= 42.025 + 0.319 + 7.796 + 2.913$
$= 53.053W$

So, from above calculations C.O.P of this device observed 0.53 in this case maximum cold side temperature observed is 5^{0}C in 20min spam, hot side (heat sink with cooling fan (forced convection heat transfer mode)) sink temperature found 42^{0}C in practical condition.

VII. CONCLUSION

In this paper a USB powered portable thermoelectric cooling system with DC to DC boost converter was designed and developed, tested in theoretical and practical model. Basing on both test results the cooling system is capable of attaining cooling temperature up to 5^{0}C in ideal condition at ambient temp 32^{0}C, cooling stabilizes within ten minutes with maximum 43.18W power consumption which powered on USB (⎓5V) to boost converter for optimum performance result. The system can attain a temperature difference of set target which was 10^{0}C on ambient. Excuted the set target establish the success of this project. All the components in the project had been tested individually and the results were found to be positive.

The temperature within the test bottle was measured, compared with different types of water bottle materials. In that observed optimum cooling temp of 9.7^{0}C found in copper water bottle, 11.1^{0}C in aluminum water bottle and 13.1^{0}C in PET water bottle which insulated with thermal jacket. This device is small, portable and efficient with maximum cooling capacity Q_{max} = 150 W at (ΔT =0), ΔT_{max} = 76°C and it also works on low power consumption mode depending upon contact cooling load which used in domestic and traveling applications.

VIII. RECOMMENDATIONS

Use copper and aluminum water bottles instead of PET water bottle to obtain better cooling effect, low power consumption.

Run on USB power at regular intervals to improve performance of DC-DC boost converter.

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