Thermoelectric Cooling System for a Residential Unit

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Abstract - A thermoelectric-based system is comprised of both p- and n-type materials (semiconductors) which are arranged in parallel layers and brought in contact to form a junction. Thermoelectric coolers (TEC) will pump heat at a rate proportional to the power applied and Thermoelectric generators (TEG) will generate power, provided a temperature gradient is applied across it. During summertime in Texas, the average temperature for most of the day is greater than 35, the temperature of air 20 ft below the ground is at 15℃, this temperature difference across TEG can be used to supply the required power to operate TEC. The Thermoelectric Coolers (TEC) will be in a box, which has fans on both sides and a TEC panel to provide cooling, the TEG will be attached outside in panels, connected to a fan/ pump which draws cool air from a pipeline/ ground 20 ft below, the top will in contact with hot ambient air. Work has been done on the advancement of materials to be used for thermoelectric materials, increasing the size of panels, but this paper focuses on the application of previous material knowledge, in particular, Bismuth Telluride and its alloys to develop a self-working cooling system with the use of TEC and TEG. Work has been done on whether the size, current, cost, and power requirements can be kept within a reasonable limit while optimizing performance and efficiency.

***Key Words*: Thermoelectric, Thermoelectric Generator, Thermoelectric Cooler, Bismuth Telluride, Semiconductors.**

1. INTRODUCTION

Since demand for electricity for cooling is expected to increase because of temperature increase and extreme heat events, the balance in energy delivery is likely to shift from natural gas and fuel oil used for heating to electricity used for air conditioning, which will likely affect greenhouse gas emissions. The current air-conditioning (AC) system produces cooling effect by refrigerants like Freon, Ammonia, etc based on Vapor Compression Cycle. These refrigerants can provide maximum output, but it generates harmful gas emission and results in global warming. The U.S. power grid is divided into three sections: West, East and one for the state of Texas, power generated by Texans, for Texans. The Electric Reliability Council of Texas said power supply has been low in recent years due to many forced power generation outages and record June demand. It appealed to users to reduce power consumption as much as possible by setting thermostats to 78 degrees or higher, unplugging unused devices and avoiding using large electric appliances. Refrigeration is the process of heat-removal from a space to bring it to a lower temperature than surrounding temperature. In this context, "Peltier cooling module" which works on thermoelectric refrigeration, aims to provide cooling by using thermoelectric effects rather than the more prevalent conventional methods like 'vapors compression cycle' or the 'vapor absorption cycle'. The three types of thermoelectric effect are Seebeck effect, Peltier effect, and Thomson effect. From these three effects, Thermoelectric cooler works on the Peltier effect, which states that when voltage is applied a semiconductor, heat is absorbed from one junction and heat is rejected at another junction. Thermoelectric generator works on Seebeck effect which is the opposite of Peltier effect.

During summertime in Texas, the average high temperatures are 30°C to 36.7°C, while the average low temperatures are between 19.4°C to 24.4°C and the typical day last for about 6 hours at maximum temperature difference. The ground temperature at depths greater than 15 feet remains relatively constant through the year. At a depth of 20 feet (6.04 m), the average ground temperature is 15°C in summer and 18.37°C in winter. The TEG provides an electric current if a temperature difference is applied across it, the difference in temperature of ambient air and ground air temperature at depth greater than 10 feet is used as input to TEG, the current is then used to operate TEC for cooling. As during summer, in Texas average temperature is between 32-36 °C on an average 6-7 hours a day for approximately 3 months, this fact can be used to provide self-sufficient cooling saving money and reducing greenhouse gas emissions.

1.1 Assumptions

Room size and cooling power required: For purpose of this paper, I am going to consider cooling required for a suburban residential home, first floor which includes kitchen, living room, foyer, and a guest room, figure shown below. The average dimensions (according to data provided online) of the entire room (which includes kitchen, living room, foyer, and a guest room) is 1500 sqft, with an average ceiling height of 10ft. For a family of 5, the maximum cooling required for the room is 15000 Btu/hr or 3KW.

Fig. 1 Example of first floor-residential home.

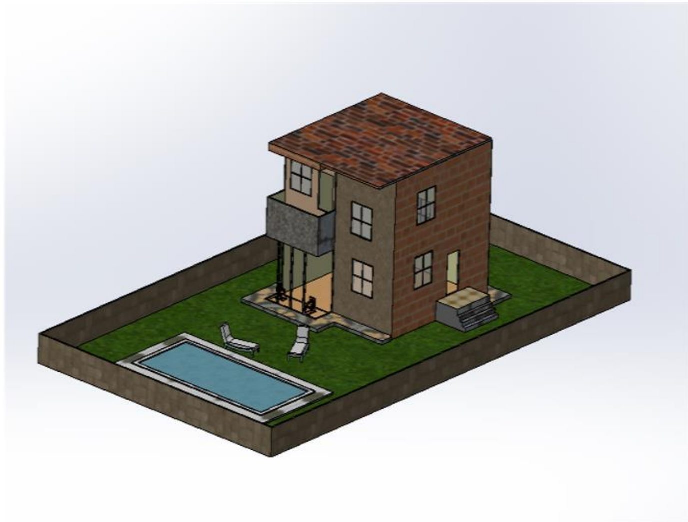

Fig. 2 Reference residential unit.

2. Design

2.1 Design of TEC panel.

The Peltier effect occurs whenever electrical current flows through two different semiconductors, which states that when voltage is applied across a semiconductor, heat is absorbed from one junction and heat is rejected at another junction. Within the world of thermoelectric technology, semiconductors made up of Bismuth Telluride and blends are the fabric of choice for producing the Peltier effect because they'll be more fluently optimized for pumping heat. Using this kind of fabric, a Peltier device (i.e., thermoelectric module) are frequently constructed in its simplest form around one semiconductor "bullet" which is soldered to electrically conductive material on each end (generally plated bobby). During this configuration, the alternate different material needed for the Peltier effect, is that the bobby connection paths to the installation force. It's important to notice that the warmth/heat is going to be moved within the direction of charge carrier movement throughout the circuit (actually, it's the charge carriers that transfer the heat). For producing the Peltier effect, semiconductor amalgamation accoutrements, like Bi2Te3 and PbTe, are better than metals. A typical TE module generally consists of the numerous n- type and p- type bulk semiconductor thermoelements that are connected electrically periodical and thermally in resemblant and squeezed between two ceramic plates. By arranging N and P-type bullets in a veritably "couple" and forming a junction between them with a plated bobby tab, it's possible to configure a circuit which may keep all the warmth residency the identical direction. As shown within the illustration, with the free (bottom) end of the P- type bullet connected to the positive voltage eventuality and thus the free (bottom) end of the N- type bullet also connected to the negative side of the voltage. As we have got seen in former section, for N-type of semiconductor, heat is absorbed from the junction around the negative terminal and warmth is releases at the junction close to the positive outstation. For P- type of semiconductor, heat is absorbed from the junction just about positive terminal and released at the junction with respects to negative terminal. By arranging the circuit as like in figure below, it's possible to release heat to the one side and absorb from another side.

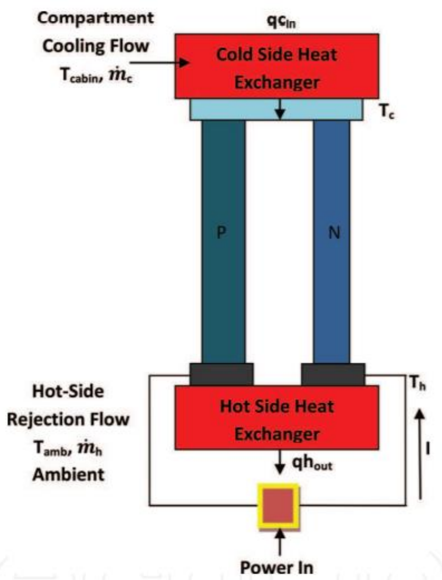

Fig. 3 Principle of thermoelectric coolers utilizing semiconductor Peltier effects.

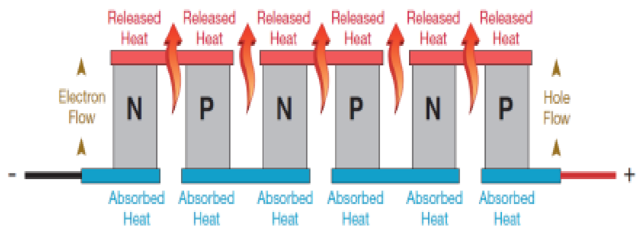

Fig. 4 Thermoelectric modules.

2.1.1 Fabrication of Peltier cooler.

As we've seen in former section, for producing thermoelectric effect couples of P and N type semiconductors are connected in series by essence of plates. By doing this it absorbs the heat from one side and releases the heat to another side. So, when solid state P-N accoutrements are connected electrically in series and thermally in resemblant it makes one thermoelectric unit as shown in Figure6. A typical TEC module comprises of two largely thermally conductive substrates (A12O3, AlN, BeO) that serve as Hot/ Cold plates. An array of p- type and n- type semiconductor (Bi2Te3, Sb2Te3, Bi2Se3, PbTe, Si-Ge) bullets are connected electrically in series squeezed between the substrates. The device is typically attached to the cold side of the TEC module, and a heat sink which is needed for enhanced heat dispersion is attached to the hot side. Solder is typically used to connect the TEC rudiments onto the conducting pads of the substrates. The construction of a single stage thermoelectric module is shown in Figure below.

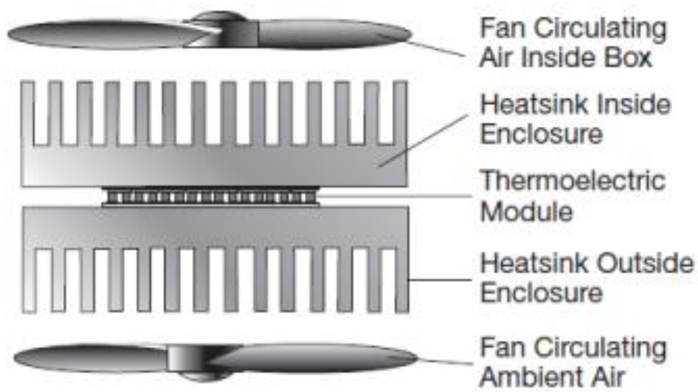

Fig. 5 TEC Cooling enclosure.

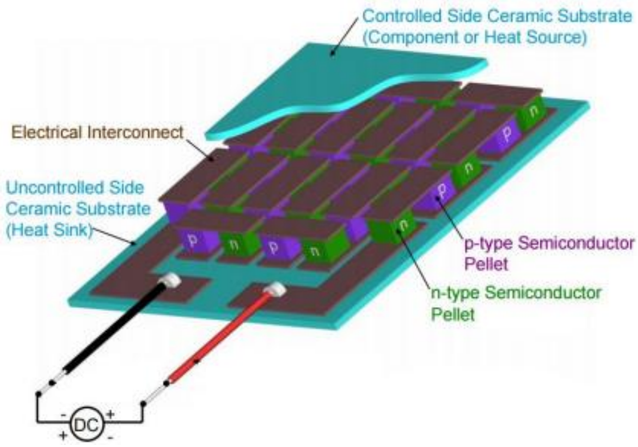

Fig. 6 TEC Cooler module.

Considering a typical thermoelectric system designed to cool air in a quadrangle (e.g., easy street box, outfit quadrangle.) is presumably the most common type of TE operation. Then the challenge is to "gather" heat from the inside of the box, pump it to a heat exchanger on the outside of the box, and release the collected heat into the ambient air. Generally, this is done by employing two heat sink/ addict combinations in confluence with one or further Peltier bias. One of the heat sinks is used on the inside of the quadrangle; cooled to a temperature below that of the air in the box, the sink picks up heat as the air circulates between the fins. In the simplest case, the Peltier device is mounted between this "cold side" sink and a " hot side" sink. As direct current passes through the thermoelectric device, it laboriously pumps heat from the cold side sink to the one on the hot side. The addict on the hot side also circulates ambient air between the sink's fins to absorb some of the collected heat. Note that the heat dissipated on the hot side not only includes what's pumped from the box, but also the heat produced within the Peltier device itself (V x I).

2.1.2 Semiconductor Materials.

Bismuth telluride is a narrow gap concentrated semiconductor with a trigonal unit cell. The valence and conduction band structure can be described as a numerous-ellipsoidal model with 6 constant- energy ellipsoids that are centered on the reflection planes. Bi2Te3 cleaves fluently along the trigonal axis due to Van der Waals relating between bordering tellurium tittles. Due to this, bismuth-telluride- grounded accoutrements are used for power generation or cooling operations must be polycrystalline. Likewise, the Seebeck measure of bulk Bi2Te3 becomes compensated around room temperature, forcing the accoutrements used in power- generation bias to be an amalgamation of bismuth, antimony, tellurium, and selenium. For my design I'm going to use Bi2Te3 (Bismuth Telluride) blends as my semiconductor. The properties are listed below:

	Type	Temperature (K)	$\|\alpha\|$ (μV/K)	σ $(\Omega cm)^{-1}$	k_e (W/mK)	k (W/mK)	ZT
Bi_2Te_3	p-type single crystals	300	230	500	0.6	2.0	0.5
BiSbTe	p-type, nanocomposites	400	220	700	0.6	1.0	1.4
$Bi_2Te_{2.7}Se_{0.3}$	n-type nanocomposites	400	210	700	0.6	1.2	1.0
PbTe-SrTe	p-type nanocomposites	900	270	300	0.4	1.1	2.2
$Si_{70}Ge_{30}$	n-type single crystals	1000	350	320	0.5	4.0	0.8
$Si_{80}Ge_{20}$	n-type nanocomposites	1200	250	400	0.5	2.8	1.3
$CoSb_3$	n-type single crystals	800	240	800	0.5	4.0	0.6
Yb-$CoSb_3$	n-type, Yb-filled skutterudites	800	200	1600	2.0	3.2	1.3
$Yb_{14}MnSb_{11}$	p-type, zintl compound	1200	190	200		0.7	1.1
La_3Te_4	n-type single crystals	1200	280	80	0.3	0.7	1.1

Fig. 7 Thermoelectric properties of material.

p-type: Bi2Te3

n-type: Bi2Te2.7Se0.3.

2.1.3 Semiconductor Dimensions.

According to data obtained from Sager Electronics, on average the dimensions of TEC Module are given below:

Area of TEC Module=60mm*60mm=3600mm^2.

Area of p type and n-type(total)=1800mm^2.

Number of p-type and n-type elements=10.

Area of p type and n-type(single)=180 mm^2.

Element Thickness=10mm

Average price=2.5$/module.

2.1.4 Simulation.

Simulation was performed using Nano Hub simulation tool, developed by Je-Hyeong Bahk, Megan Youngs, Zach Schaffter, Kazuaki Yazawa and Ali Shakouri at Purdue University. We have cooling load as 3KW, using Nano Hub, I found out the current that gives the maximum performance for required cooling at ambient temperatures from 32-36 °C. The sub tool used is thin film and multi element thermoelectric device simulator.

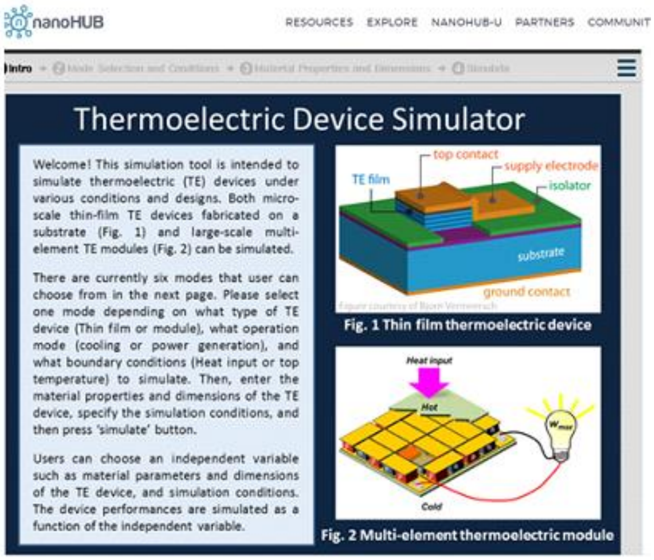

Fig. 8 Thermoelectric Nano Hub simulator.

The next part of simulation asks for mode selection and the input parameters. Select the mode 5 thermoelectric cooling where top temperature is known and electric current as independent variable from -5A to 5A. T1 is temperature inside the room, assuming the room must be kept at 300K, T1 is 300K and for T ambient we have temperatures from 32-36°C or 305K-309K. Next page asks for material properties and dimensions which can be inputted from the tables and values provided in previous sections. After entering appropriate values then we hit simulate.

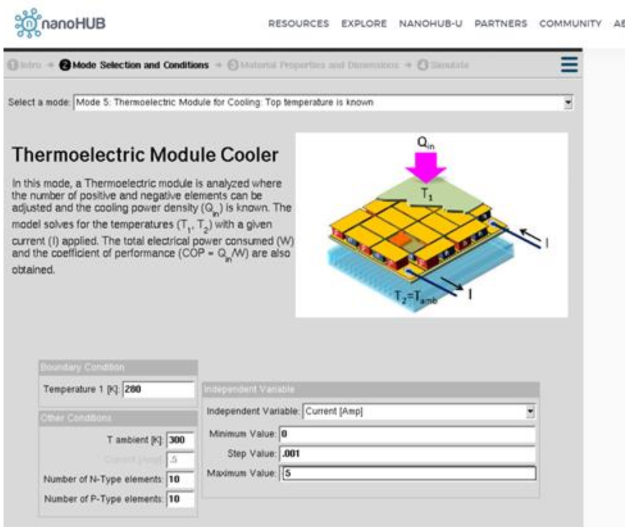

Fig. 9 Thermoelectric cooler module-Mode selection.

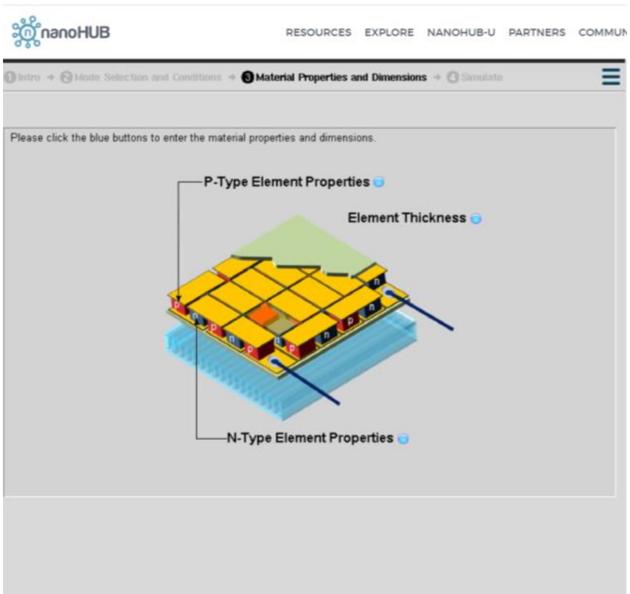

Fig. 10 Material properties and Dimensions.

2.1.5 TEC Module simulation results.

T ambient=T2=305K

Maximum COP at Current = 1.15 [Amp]

$Qc(T2 = 305K) = S * Tc * I - 0.5 * I^2 * R - K\Delta T = -0.696W$
(Substituting from values above)

So, one module can provide 0.696W of cooling, a single module cost 2.5$ on average for mass production, so to provide the required cooling of 3KW we require 4310 modules costing us 10000$.

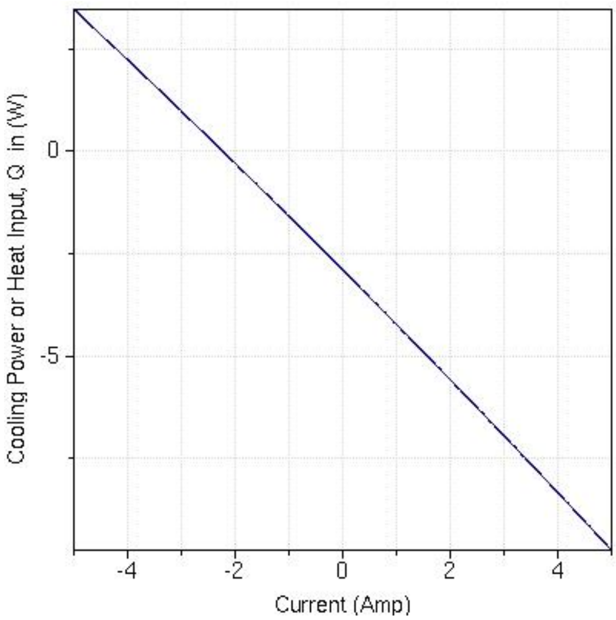

Fig. 11 Cooling power vs Current.

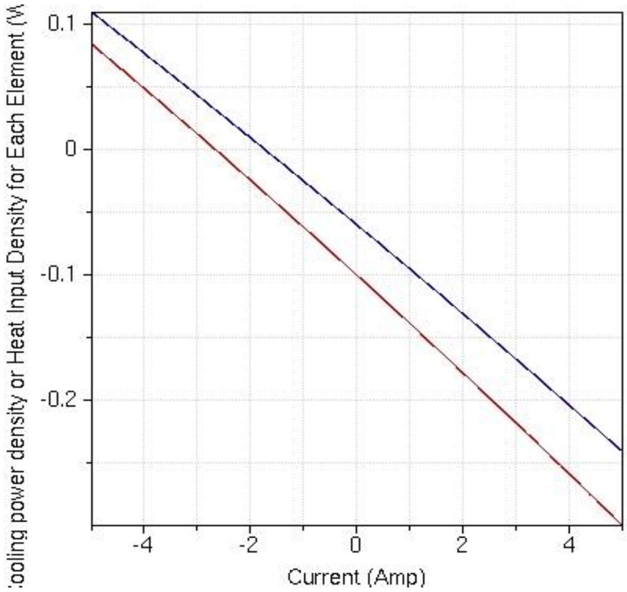

Fig. 12 Cooling power density vs Current.

T ambient=T2=306K

Maximum COP at Current = 1.38 [Amp]

$Qc(T2 = 306K) = S * Tc * I - 0.5 * I^2 * R - K\Delta T = -0.887W$
(Substituting from values above)

So, one module can provide 0.887W of cooling, a single module cost 2.5$ on average for mass production, so to provide the required cooling of 3KW we require 3382 modules costing us 8455$.

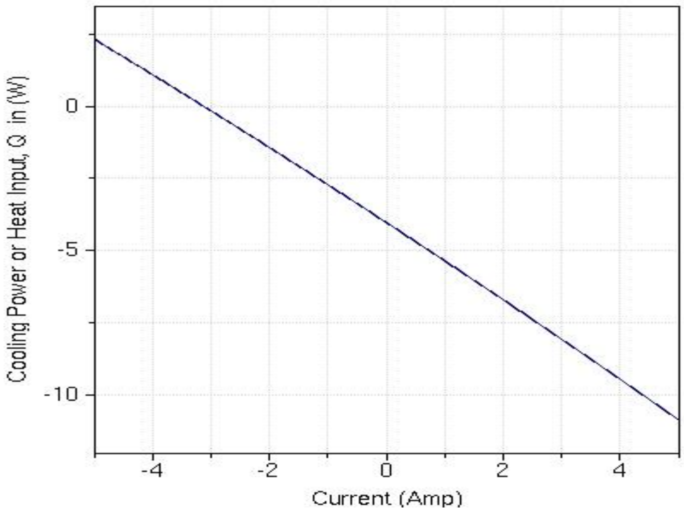

Fig. 13 Cooling power vs Current.

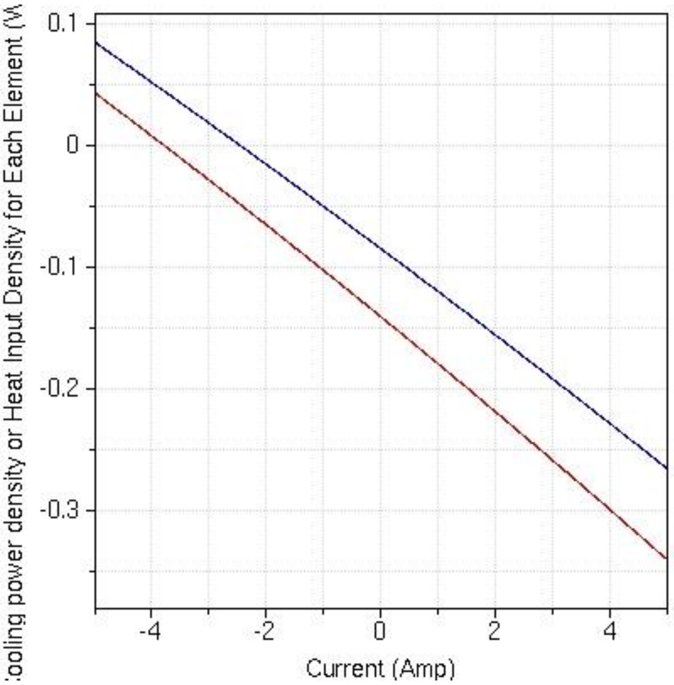

Fig. 14 Cooling power density vs Current.

T ambient=T2=307K

Maximum COP = 28797.609 at Current = 1.61 [Amp]

$Qc(T2 = 307K) = S * Tc * I - 0.5 * I^2 * R - K\Delta T = -1.1W$
(Substituting from values above)

So, one module can provide 0.887W of cooling, a single module cost 2.5$ on average for mass production, so to provide the required cooling of 3KW we require 2700 modules costing us 6800$.

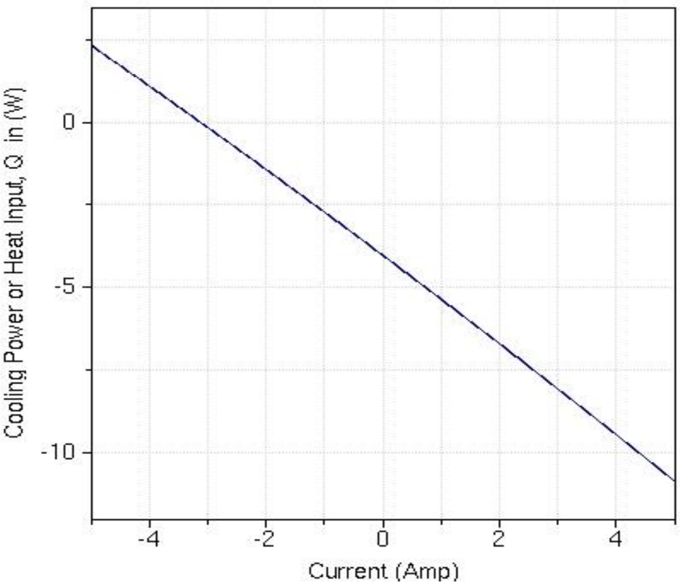

Fig. 15 Cooling power vs Current.

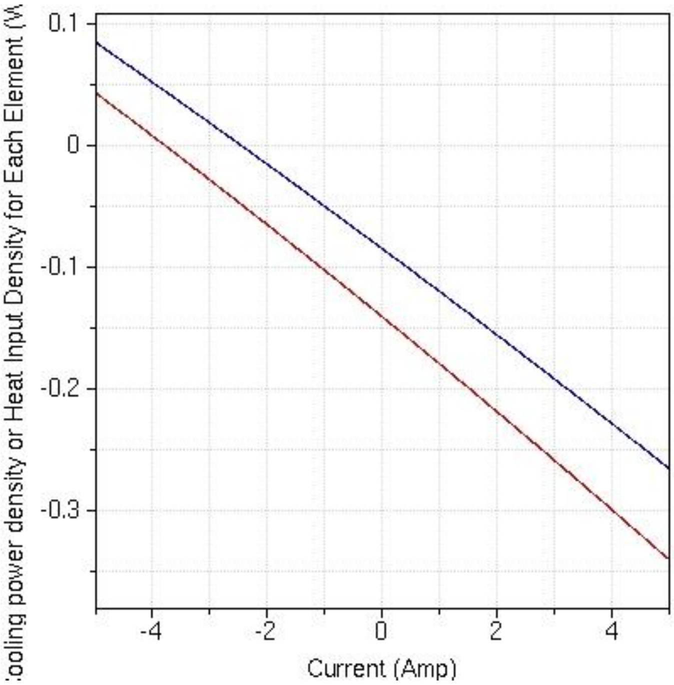

Fig. 16 Cooling power density vs Current.

T ambient=T2=308K

Maximum COP = 25212.283 at Current = 1.84 [Amp]

$Qc(T2 = 308K) = S * Tc * I - 0.5 * I^2 * R - K\Delta T = -1.32W$
(Substituting from values above)

So, one module can provide 1.32W of cooling, a single module cost 2.5$ on average for mass production, so to provide the required cooling of 3KW we require 2270 modules costing us 5500$.

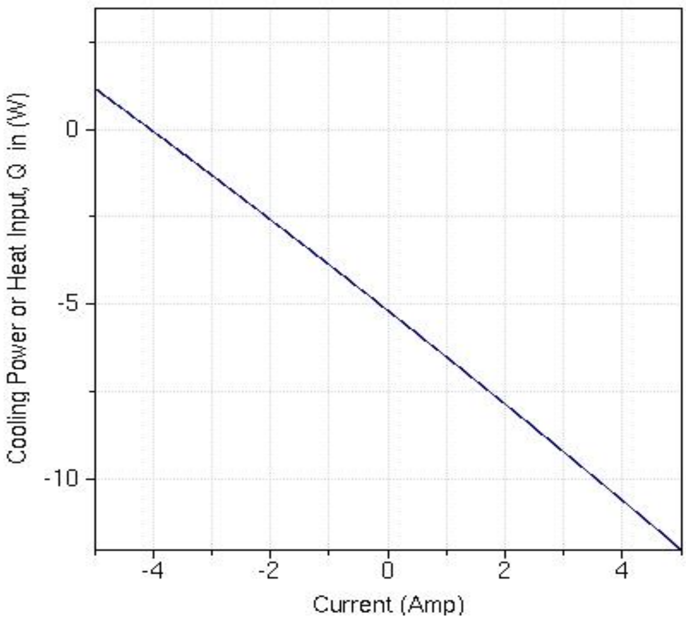

Fig. 17 Cooling power vs Current.

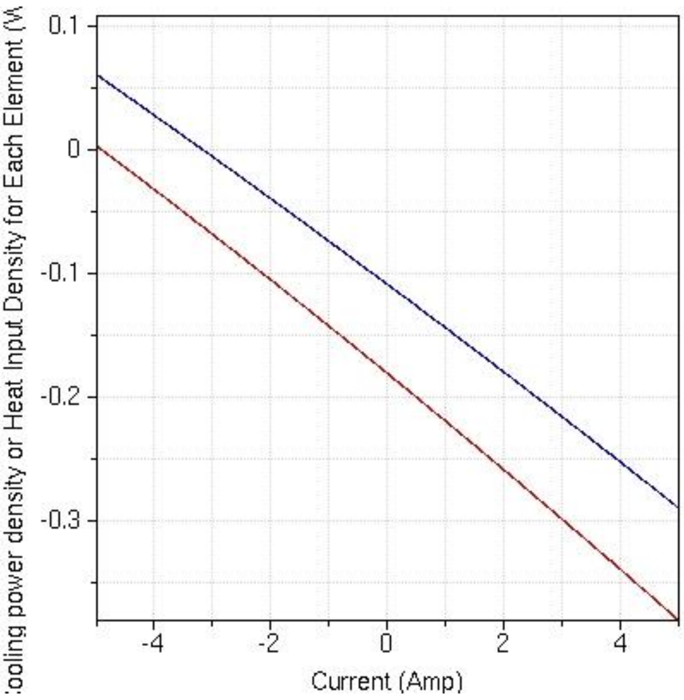

Fig. 18 Cooling power density vs Current.

T ambient=T2=309K

Maximum COP = 22423.696 at Current = 2.07 [Amp]

$$Qc(T2 = 309K) = S * Tc * I - 0.5 * I^2 * R - K\Delta T = -1.56W$$

(Substituting from values above)

So, one module can provide 1.56W of cooling, a single module cost 2.5$ on average for mass production, so to provide the required cooling of 3KW we require 1900 modules costing us 4500$.

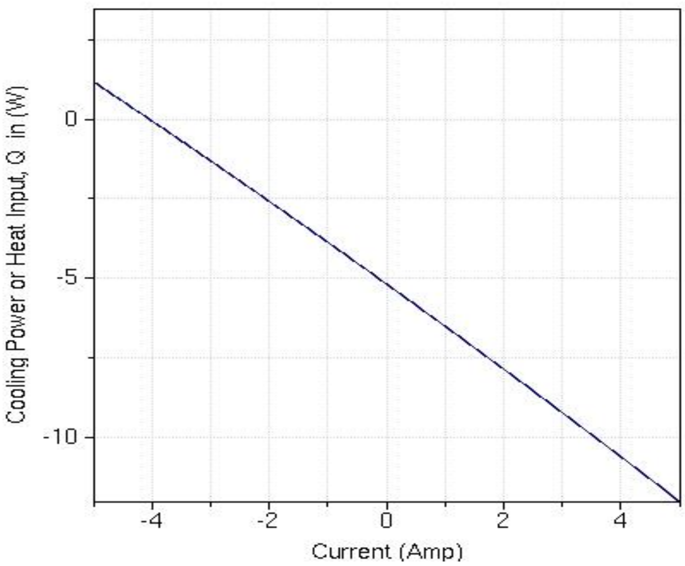

Fig. 19 Cooling power vs Current.

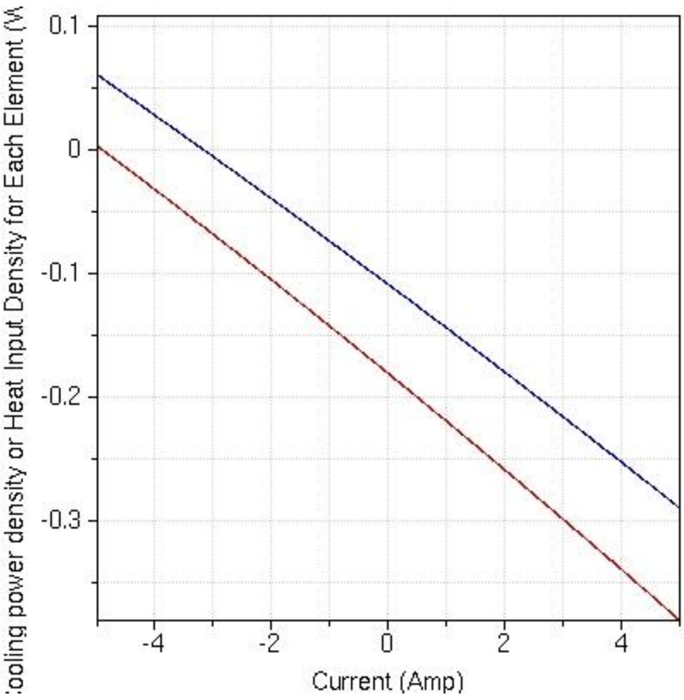

Fig. 20 Cooling power density vs Current.

The average price for the TEC setup for T=305K to 309K is 7051$ which is reasonable compared to price of an AC unit setup. The cost of AC unit which includes the cost of setup (1000$), components (6000$) and electricity for 3 months (3000$) for a same sized room, is approximately 10,000$. In summers, temperatures stay from 305K to 309K (it can also exceed 309K) 7 hours a day, which usually includes the time when most cooling is required. The current required to be generated, for maximum COP for temperature range of T=305K to 309K is I=1.15A to 2.07A. The current that we found out is the current to be generated by TEG and provide the cooling power.

2.2 Design of TEG Panel.

Thermoelectric bias are solid- state device that convert heat into electricity. When one end of a panel of TEG is connected to the air inflow at an average temperature of 15degC from the ground beneath at 10-15 bases, and the other end to the ambient air temperature, the heat flows through the TEG, creating a temperature grade across the device. Depending on the Seebeck effect of the element accoutrements (p-and n-type thermoelectric accoutrements) of the device, power is generated commensurable to the temperature grade. The performance and effectiveness of a thermoelectric device substantially depends on two aspects videlicet, the thermoelectric material effectiveness and the design optimization of the device. The effectiveness of thermoelectric accoutrements is determined by the figure of merit, ZT = α 2σT/ κ, where α is the Seebeck measure, σ is the electrical conductivity, T is the absolute temperature and κ is the thermal conductivity of the material. For a material to have a better ZT, it's needed to have high electrical conductivity along with a high Seebeck measure and low thermal conductivity. The other aspect of the device performance is the device design, which also plays a significant part in rooting the maximum possible power for a given script. This design is associated with colorful design parameters of the device to enhance the power affair as well as the effectiveness of the energy conversion.

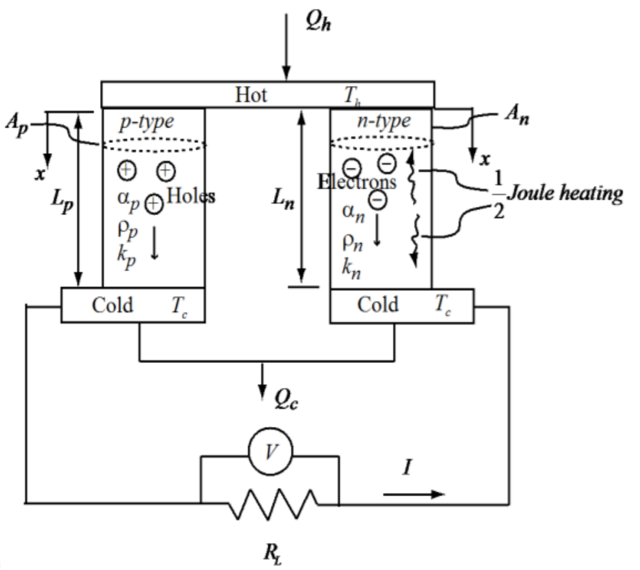

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Fig. 21 Couple leg TEG module with heat transfer.

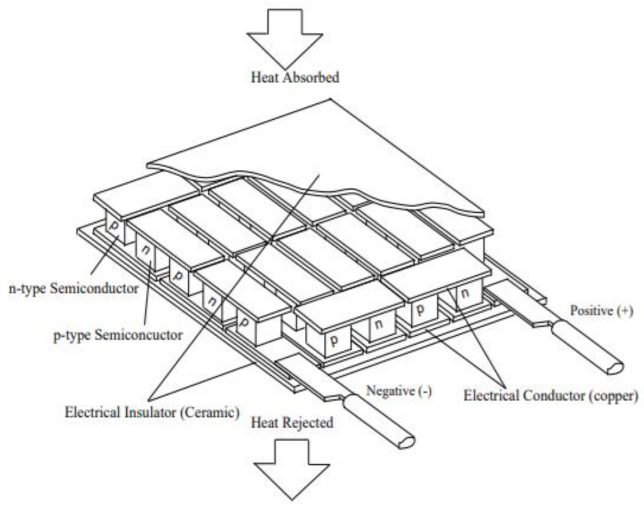

Fig. 22 TEG Module.

Given Conditions:

Ts=Temperature at hot side=305K-309K.

Td=Temperature at cold side=288K.

Area of p type and n-type(total)=1800 mm^2.

Number of p-type and n-type elements=50

Area of p type and n-type(single)=180 mm^2.

Element Thickness=10mm.

p-type: Bi2Te3

n-type: Bi2Te2.7Se0.3.

Design Equations:

p-side $Qhp = Sp * Th * I - 0.5 * I^2 * Rp - Kp * \Delta T$

n-side $Qhn = -Sn * Th * I - 0.5 * I^2 * Rn - Kn * \Delta T$

Qh=Qhn+Qhp= $S * Tc * I - 0.5 * I^2 * R - K\Delta T$

$P(Power) = I * (S * \Delta T - I * R)$

$\delta(effeciency) = P/Qh$

$$ZT = S^2 * \frac{T}{R * K}$$

S=Sp-Sn=230 μV/K -(-210) μV/K =440 μV/K

$$\mathrm{R} = \mathrm{Rp} + \mathrm{Rn} = \frac{\mathrm{Lp}}{\mathrm{Ap} * \sigma\mathrm{p}} + \frac{\mathrm{Ln}}{\mathrm{An} * \sigma\mathrm{n}} = 0.323\mathrm{ohm}$$

$$\mathrm{K} = \mathrm{Kp} + \mathrm{Kn} = \frac{\mathrm{kp} * \mathrm{Ap}}{\mathrm{Lp}} + \frac{\mathrm{kn} * \mathrm{An}}{\mathrm{Ln}} = 0.1273\mathrm{W/mK}$$

T1= Temperature of hot air outside= 305K-309K

T ambient = Temperature of air inside the ground = 288K

ΔT=Th-Tc= 5K and 9K.

2.3 Simulation:

Using Nano Hub simulation tool- Thin film multielement thermoelectric device simulator:

Model selections and conditions-Mode 6 Thermoelectric module for power generation-Top temperature is known.

T1=305K-309K, T ambient = Temperature of air inside the ground = 288K, Independent variable=Current from -5A to 5A with an interval of 0.01A.

In the material properties and dimensions, from the table put in for p properties of Bi2Te3 and Bi2Te2.7Se0.3 for n.

T1=305K

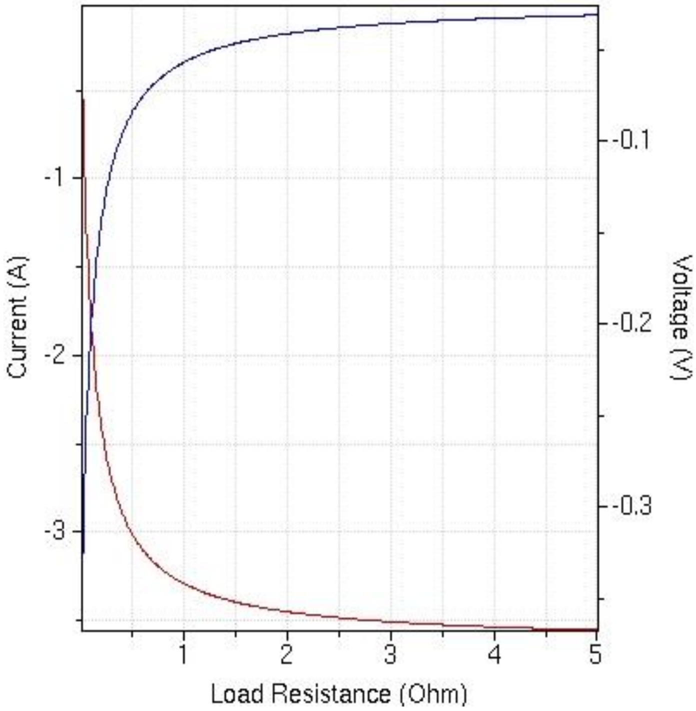

Fig. 23 Load Resistance vs Current.

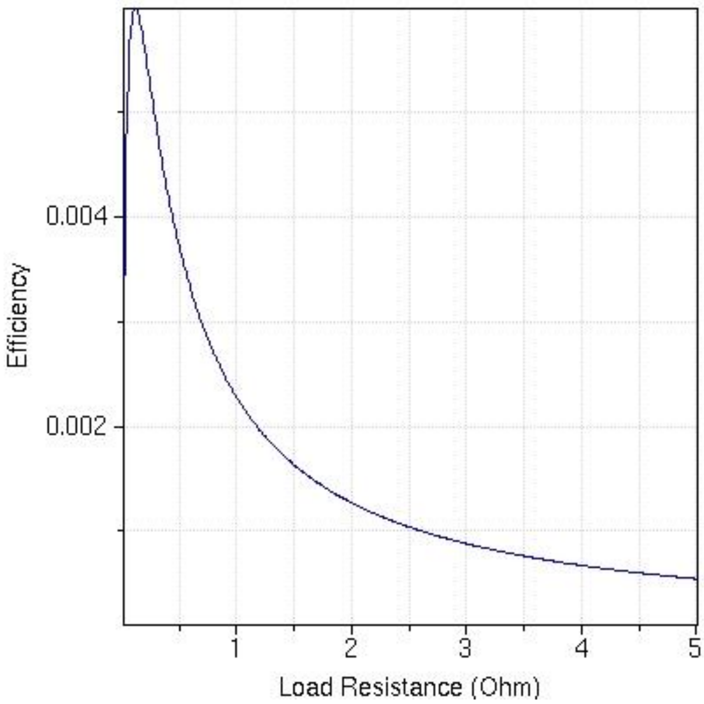

Fig. 24 Load resistance vs Efficiency.

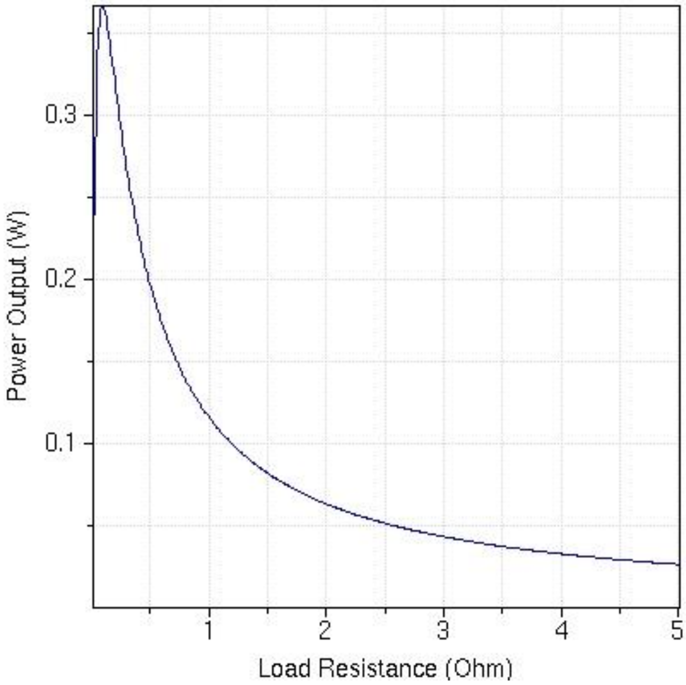

Fig. 25 Load Resistance vs Power Output.

Maximum Power Output = 3.670e-01 [W] at Load Resistance = 0.100000 [Ohm]

Maximum efficiency = 5.991e-03 at Load Resistance = 0.120000 [Ohm]

Total internal resistance = 9.524e-02 [Ohm]

$P = I^2 * R$

I=1.9 A

When T2= Ambient Temperature= 305K, Maximum COP at Current = 1.15 [Amp] for TEC. As we can see that current generated by TEG (1.9A) is greater than and sufficient to provide a current of 1.15A to the TEC panel.

P=3KW, number of TEG modules required are 8170, costing around 20425$.

T1=306K

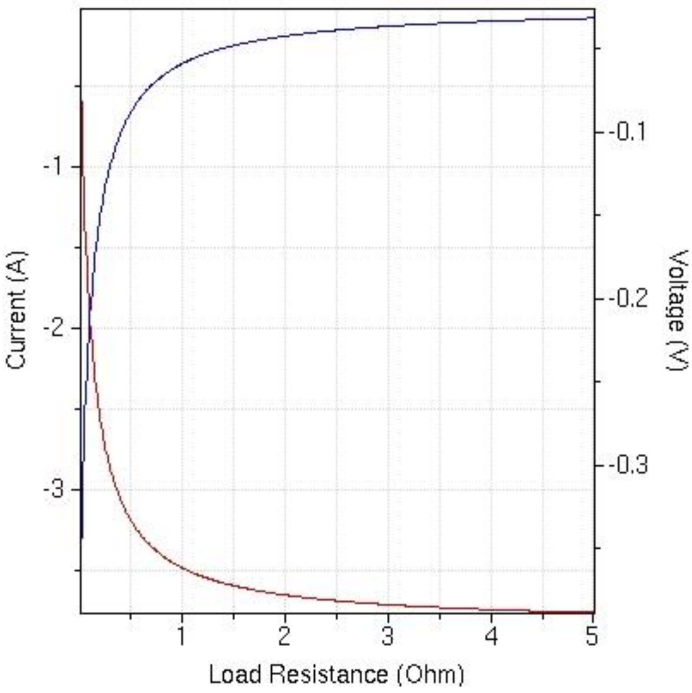

Fig. 26 Load Resistance vs Current

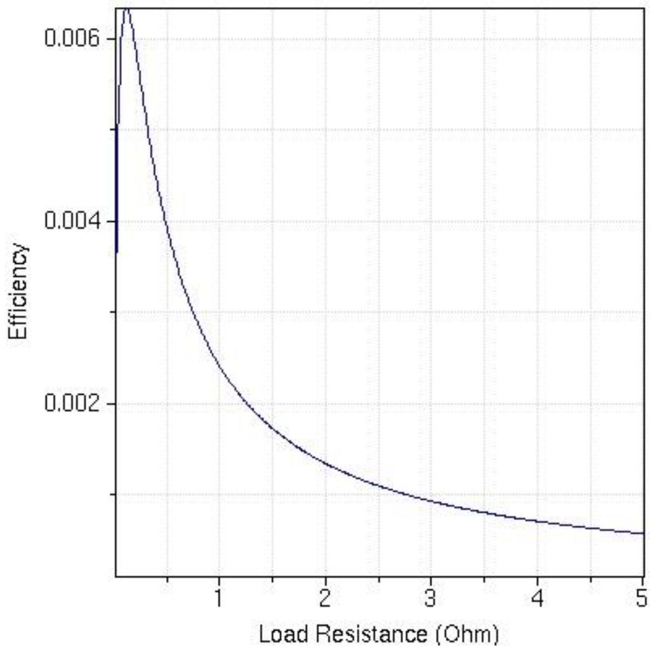

Fig. 27 Load resistance vs Efficiency.

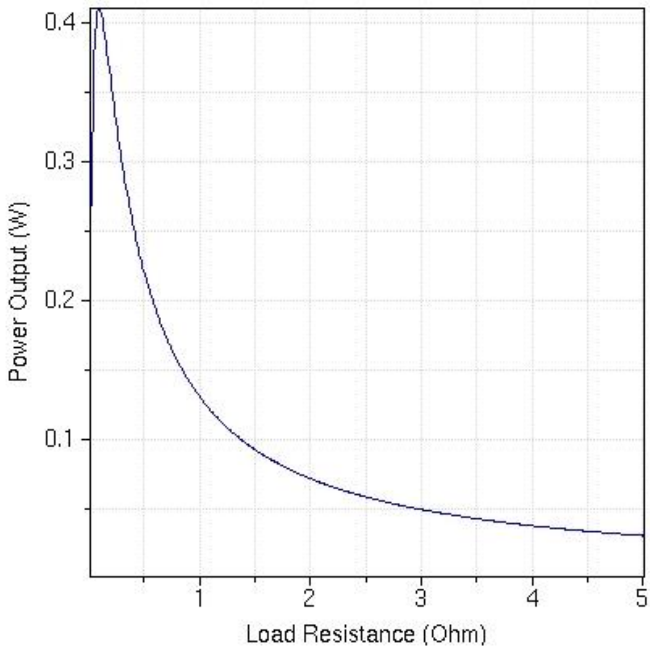

Fig. 28 Load Resistance vs Power Output.

Maximum Power Output = 4.114e-01 [W] at Load Resistance = 0.100000 [Ohm]

Maximum efficiency = 6.340e-03 at Load Resistance = 0.120000 [Ohm]

Total internal resistance = 9.524e-02 [Ohm]

$$P = I^2 * R$$

I=2.02 A

When T2= Ambient Temperature= 306K, Maximum COP = 33578.043 at Current = 1.38 [Amp]. As we can see that current generated by TEG (2.02 A) is greater than and sufficient to provide a current of 1.38A to the TEC panel.

P=3KW, number of TEG modules required are 7290, costing around 18000$.

T1=307K

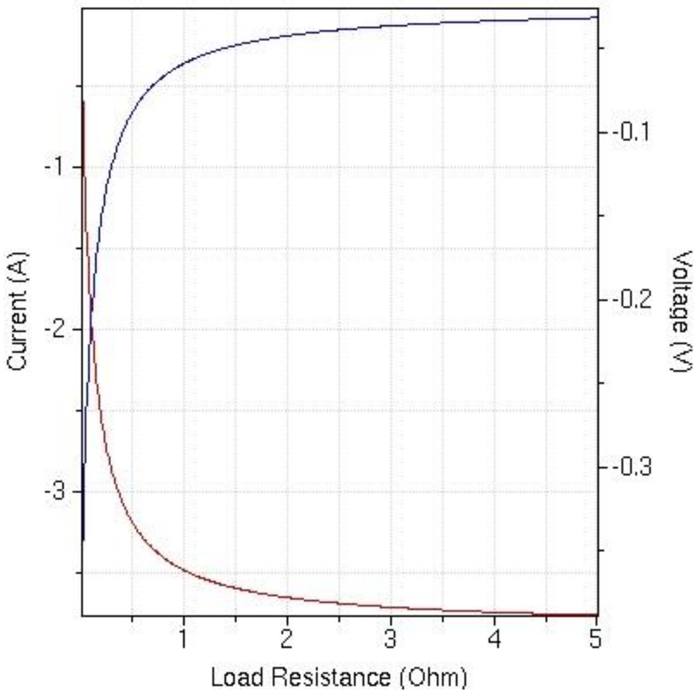

Fig. 29 Load Resistance vs Current

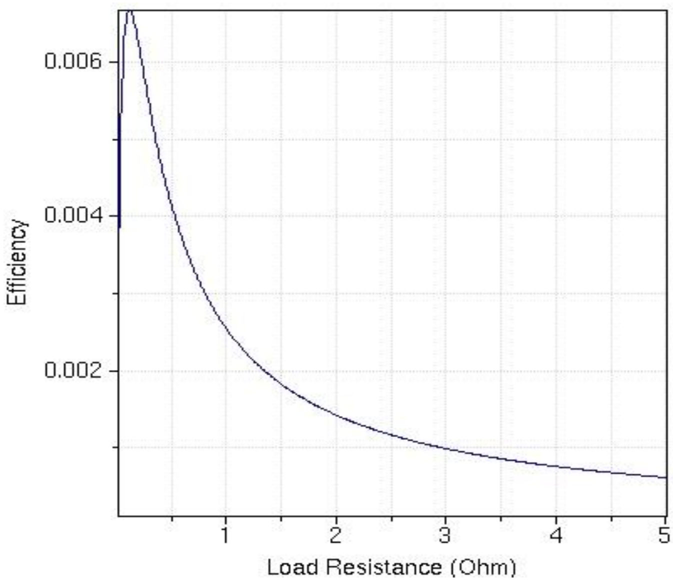

Fig. 30 Load resistance vs Efficiency.

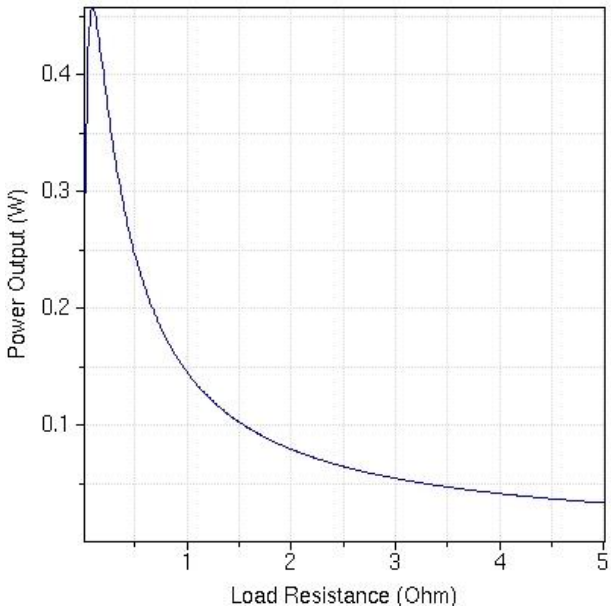

Fig. 31 Load Resistance vs Power Output.

Maximum Power Output = 4.584e-01 [W] at Load Resistance = 0.100000 [Ohm]

Maximum efficiency = 6.689e-03 at Load Resistance = 0.120000 [Ohm]

Total internal resistance = 9.524e-02 [Ohm]

$P = I^2 * R$

I=2.141 A

When T2= Ambient Temperature= 307K, Maximum COP = 28797.609 at Current = 1.61 [Amp] for TEC. As we can see that current generated by TEG (2.141A) is greater than and sufficient to provide a current of 1.61A to the TEC panel.

P=3KW, number of TEG modules required are 6200, costing around 15495$.

T1=308K

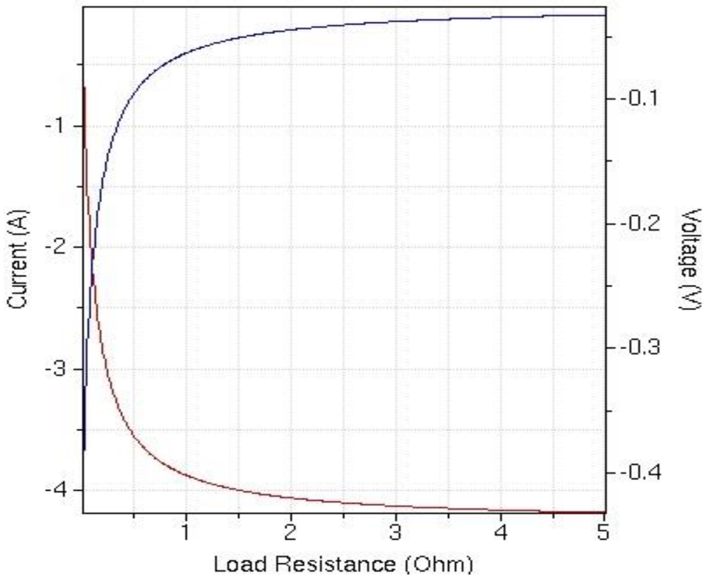

Fig. 32 Load Resistance vs Current

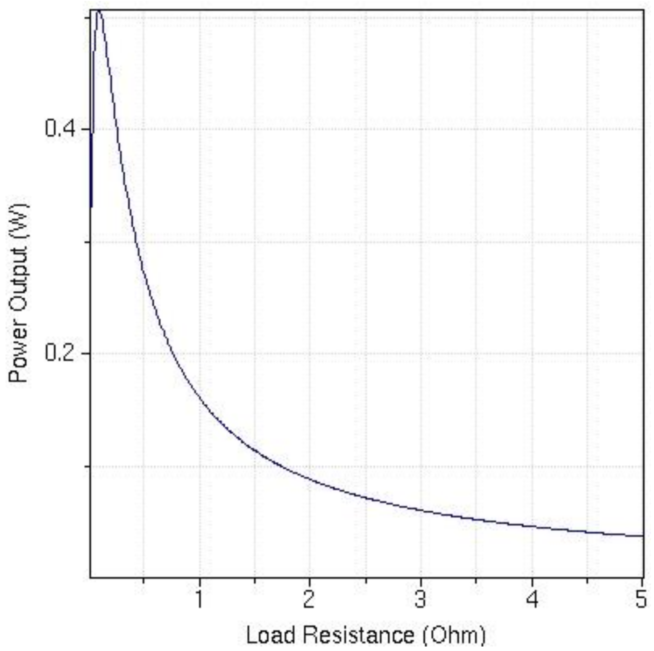

Fig. 34 Load Resistance vs Power Output.

Maximum Power Output = 5.079e-01 [W] at Load Resistance = 0.100000 [Ohm]

Maximum efficiency = 7.038e-03 at Load Resistance = 0.120000 [Ohm]

Total internal resistance = 9.524e-02 [Ohm]

$P = I^2 * R$

I=2.25A

When T2= Ambient Temperature= 308K, Maximum COP = 25212.283 at Current = 1.84 [Amp] for TEC. As we can see that current generated by TEG (2.25A) is greater than and sufficient to provide a current of 1.84A to the TEC panel.

P=3KW, number of TEG modules required are 5900, costing around 14766$.

T1=309K

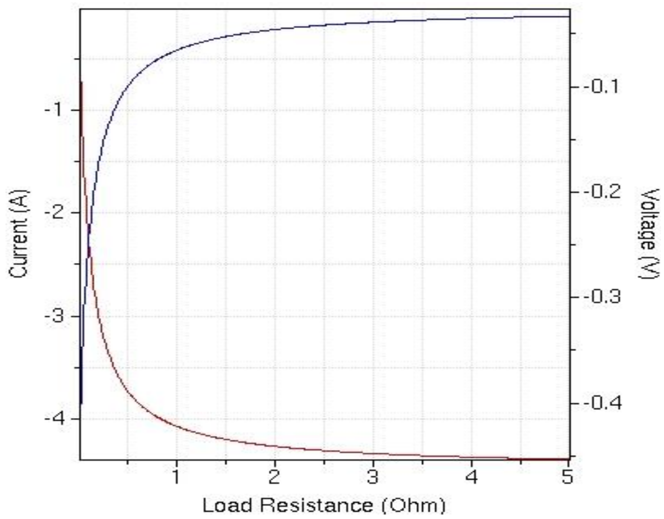

Fig. 35 Load Resistance vs Current

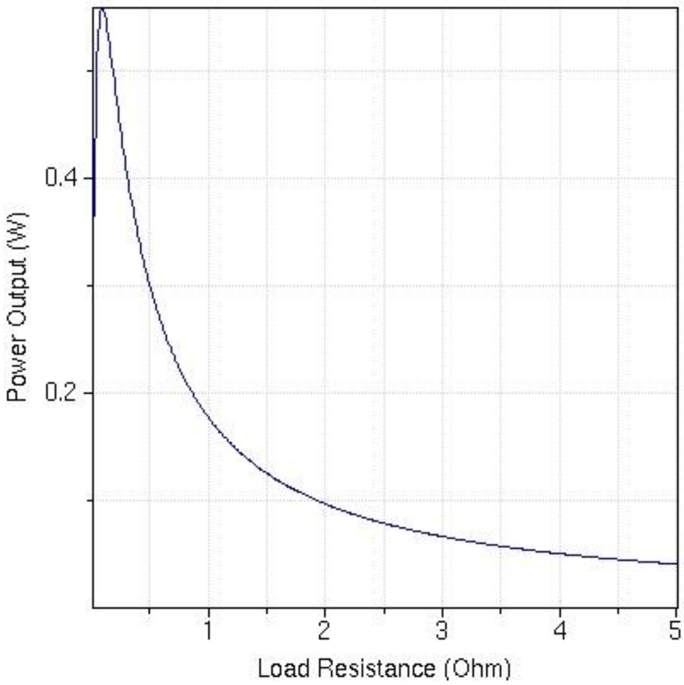

Fig. 36 Load resistance vs Power Output.

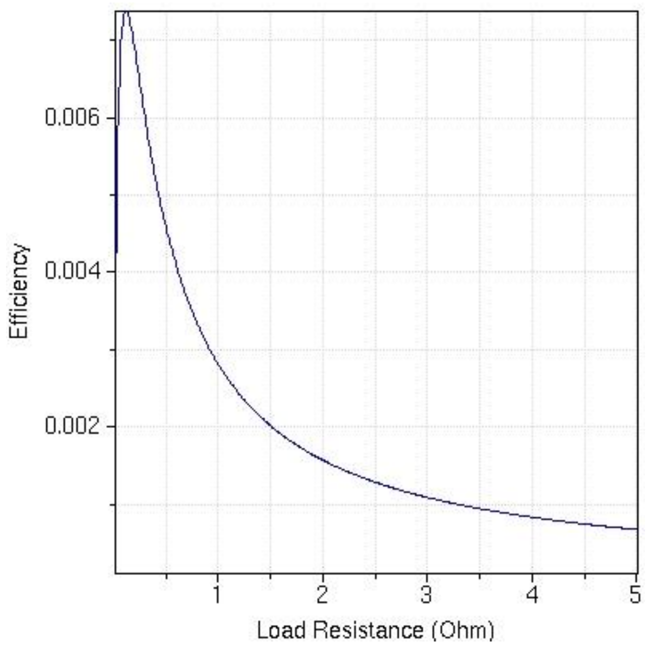

Fig. 37 Load Resistance vs Efficiency.

Maximum Power Output = 5.600e-01 [W] at Load Resistance = 0.100000 [Ohm]

Maximum efficiency = 7.386e-03 at Load Resistance = 0.120000 [Ohm]

Total internal resistance = 9.524e-02 [Ohm]

$P = I^2 * R$

I=2.36A

When T2= Ambient Temperature= 309K, Maximum COP = 22423.696 at Current = 2.07 [Amp] for TEC. As we can see that current generated by TEG (2.36A) is greater than and sufficient to provide a current of 2.07A to the TEC panel.

P=3KW, number of TEG modules required are 5357, costing around 13392$.

3. CONCLUSIONS

Cost and size analysis of TEG and TEC:

Ambient temperature/ temperature of the surrounding/outside. (K)	TEG current produced. (A)	TEC current required. (A)	Total setup cost.
305K	1.9	1.15	30425$
306K	2.02	1.38	26455$
307K	2.141	1.61	22295$
308K	2.25	1.84	20266$
309K	2.36	2.07	17892$

From the simulation results we can observe that it is possible to design and operate a self-sufficient thermoelectric cooling and power generating system. When cooling load is low, excess power generated by the TEG can be stored in batteries. This cooling system is environmentally friendly, has no green house gas emissions and electricity cost. The major disadvantages are that it can only be operated when the temperature difference is high enough and the setup cost is very high compared to a traditional AC unit. Further research into optimizing the material and manufacturing costs needs to be done before it can be used practically.

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