POWER GENERATION BY CONDUCTING STUDY OF RECOVERING WASTE HEAT USING A TEG.

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Abstract: Automobile emissions heat is a growing menace throughout the world. A recent report by the United Nations states that without new policies, transport emissions heat may grow faster than others. This project presents the repercussions faced by automobile emissions and a method to contain it while achieving a small percentage of efficiency. Our aim is to trap exhaust heat from an automobile engine and translate it into useful work using thermoelectric generators. The project essentially involved developing a setup that enables study of the heat recovery characteristics of the thermoelectric generator module.

Keywords: Thermoelectric generator, Direct energy conversion, Thermoelectric material, Figureof merit, Waste heat recovery,Seebeck effect.

1. LITERATURE SURVEY

To carry out the study as my project, some technical research papers were referred to specify work done upon waste heat recovery using thermoelectric generators. All basic concepts of the thermoelectric generator are generally known, but now will have a review upon literature available regarding our study. Since 1980 thermoelectric generators are inspected experimentally for power generation using waste heat. Firstly Rowe et al. studied this area with immense interest and depth in 1997. A system consisting of 36 TEGs modules sandwiched among 2 aluminum heat exchangers was constructed. A heat exchanger was brought into existence by maintain a source of heat at 98℃ in form of hot water and the other end at 20℃ in form of cold water. Upon maintain temperature combinations at 97℃ max and 14℃ as cooler end resulted in 95 watts of maximum power generation. By this study being carried out these TEGs were able to translate waste heat into useful power at low efficiency. It was concluded that conversion efficiency cannot be considered as the source of heat in this was free available [1].

2. INTRODUCTION

2.1 Energy:

Heat is a kinetic energy that transfers from one source of energy to another. Heat transfers from a body of higher temperature to that of lower one by transmitting of matter or by external force.This happens in accordance, due to existence of anappropriate physical laneamong the bodies. Second law of thermodynamics facilitates this phenomenon.

2.1.1 Units andRepresentation:

Since Heat is a type of energy is scaled using a unit. The standard unit of Heat Energy is Joule as a SI unit and calorie as a BT unit. When it comes to the transmission or motion of heat it is rated per unit time know as Watt also known as joules per unit time.

Is denoted by $\dot{Q}$ [11].

2.1.2 Modes of HeatTransfer:

The three main means of transfer of heat are:

- ✓ Conduction,
- ✓ Convection,
- ✓ Radiation.

2.1.2.1 Conduction:

Conduction is a thermal phenomenon which comprises transfer of energy by physical contact among particles or quasi-particles inside the body

Conduction: A Particle ViewAny matter present comprises of particles present known as wigglers and bangers. Among these wigglers are the one which vibrate at its position itself and bangers keep on moving i.e. they are translator in nature causing disturbance. So, in conduction the stationary and moving particles upon colliding exchange energy and the disturbance increases

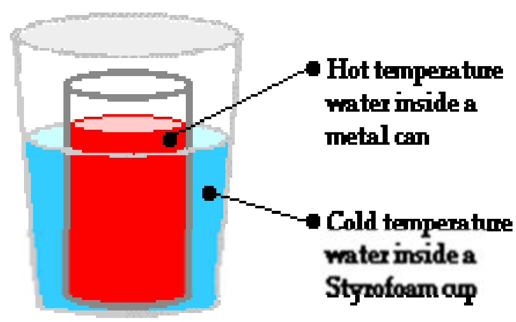


Fig 2.1 Setup for Conduction

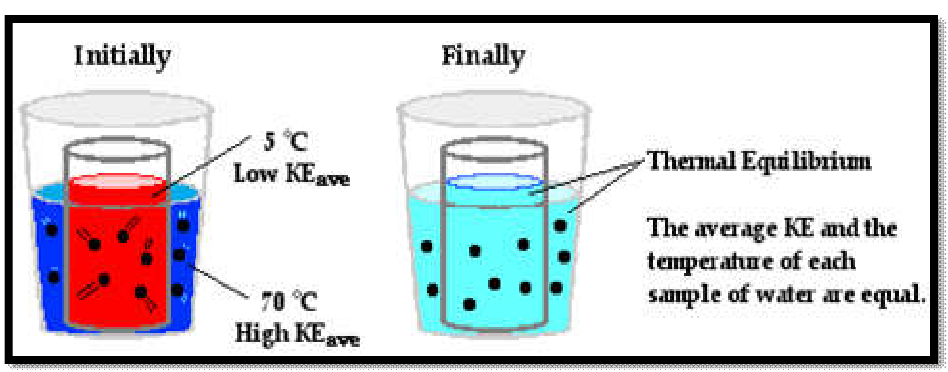


Figure 2.2 Kinetic Energy in Conduction

Fourier'slaw:

This is the law upon which the conduction relies. This law of conduction is also known asFourier's law. It is named after the famous scientist Joseph Fourier. This law states, the heat flow across a solid body is directly proportional to the cross-sectional area and the temperature gradient across the flow [12].

2.1.2.2 Convection:

Convection is a thermal phenomenon which comprises transfer of heat without physical contact. This is generally across fluids. Convection occurs between various states of matter. Even here the convection occurs in between the two bodies at different temperatures i.e. from areas at higher temperature to one at lower temperature. The fluid attaining higher temperature becomes lighter were as the fluid at lower temperature becomes denser. Thus, the fluid at higher temperature is pushed up by the fluid at lower temperature. This process goes on continuing as a cyclic process. Boiling milk in a kettle is a real time phenomenon of convection. Green House Effect also follows convection as its principle [10].

Principle ofconvection:

Convection in a real time application can be witnessed by boiling of milk in a kettle. To understand the convection phenomenon, arrange the kettle on the heater or stove. The heat source in direct contact to the kettle heats up the kettle. Once the kettle is heated up it starts conducting heat to milk inside the kettle. The milk at the inner surface starts getting heated up and later becomes hot. As we know fluids expand upon being heated. Also due to expansion the hotter fluids become less dense i.e. their density reduces. And the lighter fluids raise up and the cooler fluid because of being denser comes down. Now this cooler fluid starts heating up and this cycle continues. These displacements due to variation of density are known as convective currents. Thus, convection in any fluid occurs [11].

Newton's law of cooling:

Newton's law, states that temperature gradient between some system and surroundings is directly proportional to heat loss at a constant heat transfer coefficient. Convection follows this law [12].This rate of heat transfer is derived as:

$$\frac{dQ}{dt} = h \cdot A \cdot (T(t) - T_{\text{env}}) = h \cdot A \Delta T(t)$$

Here,

Q= Energy (Joules)

h =Heat transfer Coefficient $({W}/{m2\ K})$

T= Surface temperature.(K)

T_{env}= Environmental temperature. (K)

$$\Delta T(t) = T(t) - T_{\text{env}}$$

2.1.2.3 Radiation:

The third mode of heat transfer is Radiation. This phenomenon comprises of emitting electromagnetic waves. Radiation is a mode of heat transfer which is independent of physical contact i.e. source and sink are nowhere in contact, in contrast to conduction & convection. Heat transfer due to emission of electromagnetic waves is known as thermal radiation. Here this phenomenon is carried out in absence of any medium. The best example of radiation is rays heating the earth from Sun [10].

The Stefan-Boltzmann equation:
This is a principle equation of Radiation.
For Radiation between two objects at different temperatures:

$$Q = \epsilon\sigma T^4$$

Here,

$$Q = \epsilon\sigma(T_a^4 - T_b^4)$$

Q =Heat flux,
ε = Emissivity ($\varepsilon_{blackbody}$ =1),

σ = Stefan-Boltzmannconstant,

T = Absolute temperature (Kelvin/Rankin) [12].

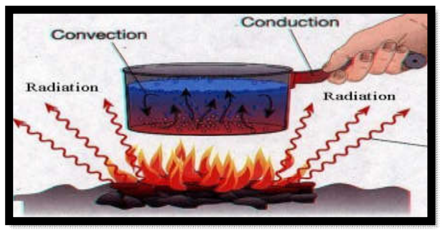


Figure 2.3 Modes of Heat Transfer

2.2 Heat Engine:

A system which translates thermal energy into useful mechanical work is a Heat Engine. This is facilitated by maintaining the temperature gradient with in a working element.

2.2.1 Working of A HeatEngine:

Complete cycle of a Heat Engine at a glance:

- ✓ Initially heat is injected which is at a higher temperature (source) (Q_H).
- ✓ In a cycle the work to be performed is also extracted from the heat injected (W).
- ✓ The remaining heat inside the system is rejected generally on the lower temperature end (sink) (Q_C).

From the Law ofConservation of Energy:

$$Q_H = W + Q_C$$

A line diagram of an ideal Heat Engine:

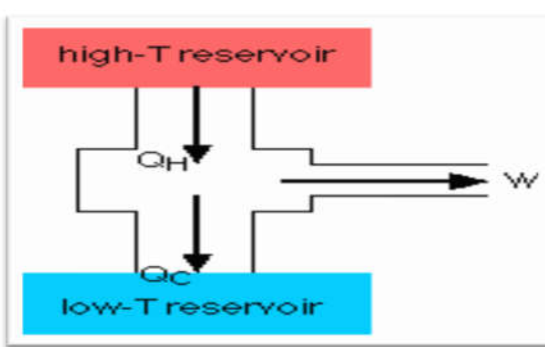


Figure 2.4 Heat Engine

2.2.2 Efficiency:

Scale toevaluate the Heat Engine is efficiency:
Efficiency:

$\eta = W / Q_H$

i.e. work done / input heat

OR $\eta = (Q_H - Q_C) / Q_H$

$= 1 - (Q_C / Q_H)$

Since work done = Heat added – Heat rejected.

This is known as Carnot efficiency which the maximum possible efficiency. Practically there is no efficiency greater than Carnot due to the losses incurred such as frictional mechanical etc [10].

2.2.3 Carnot'sPrinciple:

Heat Engine functions upon Carnot principle. Any engines working is compared and analyzed with respect to Carnot engine. Carnot engine follows a reversible process i.e. system and surrounding return to the stage they started from.

The efficiency for any engine based upon Carnot principle working across two different temperatures (T_H&T_C),Efficiency is:

$$\eta = 1 - (T_C/T_H)$$

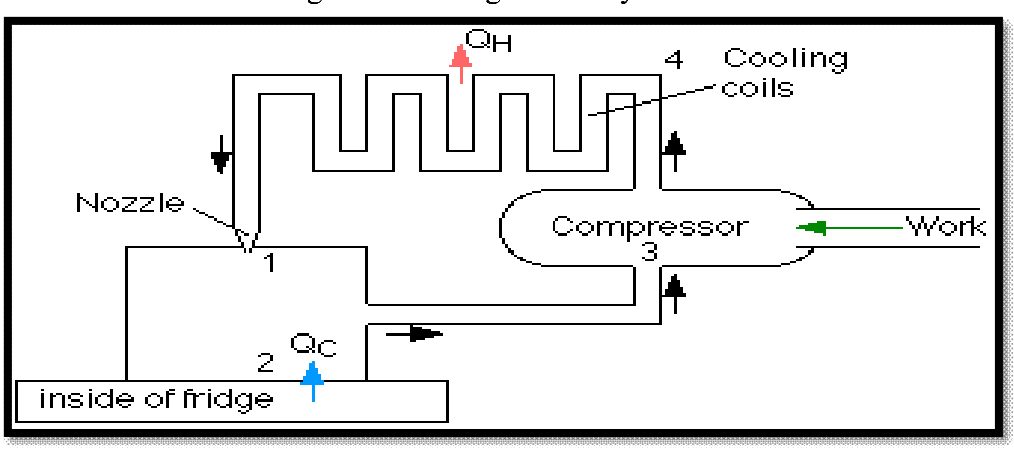
The highest efficiency is obtained by maintaining extreme hot and cold temperature at different ends[12].

2.3 Heat Pump:

Heat pump is a device which transports the fluid in a system from source to sink by consuming a portion of energy. In contrast to Heat engine this is a work consuming device. Usually Refrigerators use heat pump. The working cycle of heat pump has following stages:

- ✓ The first stage is of Adiabatic expansion. Here the working media enters a low-pressure area from a high-pressure region and suddenly expands. Upon expansion this working fluid cools down.
- ✓ This cooled fluid now comes into thermal interaction of inner components in refrigerator. Since the various components of refrigerator are at higher temperature there occurs the temperature exchange among them. This is an Isobaric Expansion process as the pressure here is constant.

Figure 2.5 Refrigeration Cycle



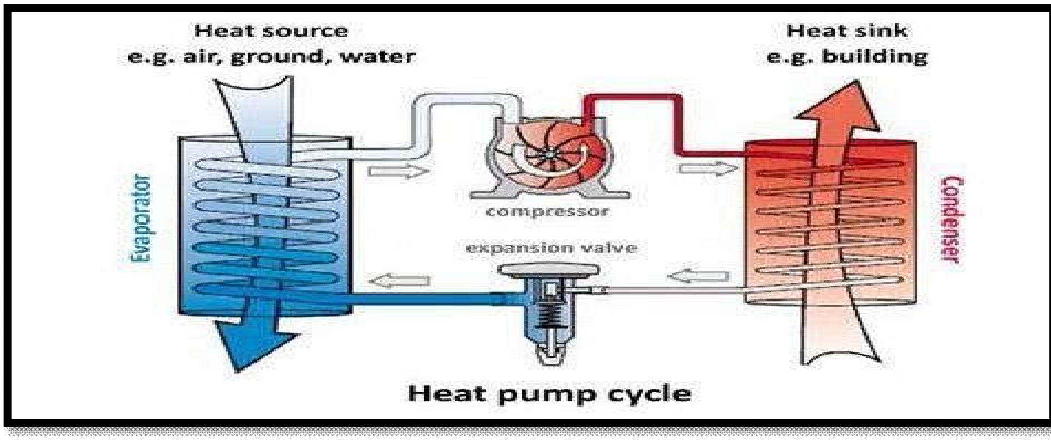


Figure 2.6 Heat Pump Cycle

2.3.1 Coefficient ofPerformance:

Coefficient of Performance is another scale of evaluation. Generally, the refrigerated is appraised using coefficient of performance. Coefficient of Performance (COP)is the ratio of Heat rejected to work consumed.

Coefficient of performance = Q_C/ W

P-V diagram of a refrigeration cycle:

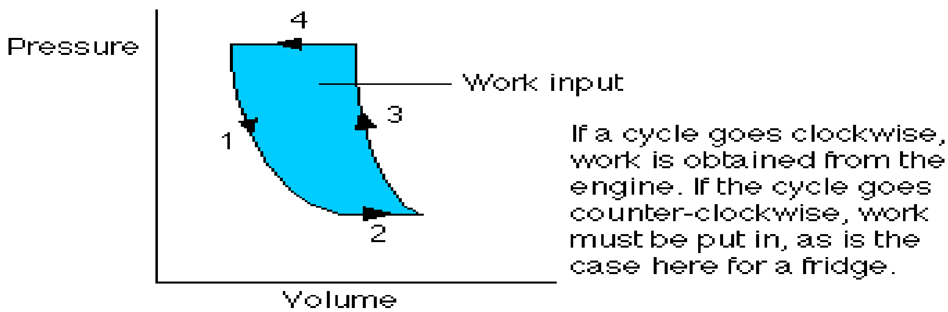


Figure 2.7 P-V Diagram of a Refrigerator

2.4 WASTEHEAT

Waste heat discusses about the energy generated in various processes and being let out without being used thoroughly. The main emerging areas of waste heat are automobile combustion exhaust, processing plant emissions, discharge of heat from the equipment's to the surroundings and many more. Upon a general over view, its observed that of the total heat energy being utilized 60-70% is flushed as waste heat. These waste heat losses from all vital sources can be regained and all these losses can be lowered. All the equipment's working performance can be rectified and the efficiency can be made much healthier by applying various new waste heat recovery technologies [12].

2.4.1 Classification of WasteHeat:

Various sources of waste heat being produced are many. And all these various sources of waste heat exist in between various temperature ranges. A careful study of the heat produced at the site is necessary to gauge the most effective method to recover the available heat [12].

Various sources of waste heat and their temperature ranges are listed below:

Sources of Waste Heat	Temperature Range (^{o}C)
Refining furnace (Nickel)	1300 –1560
Refining furnace (Aluminum)	560-670
Refining furnace (Zinc)	670-1150
Refining furnace (Copper)	670- 851
Steel furnaces	900-1000
Reverberatory furnace	950-1150
Cement Dryer	600- 750
Glass melting furnace	950-1650
Waste particles kilns	600-1050

Table 2.1 Large Temperature Range.

Various sources of waste heat at medium temperature ranges are listed below:

Sources of Waste Heat	Temperature Range (^{o}C)
Boilers	200-500
Gas Turbine emission	350-500
Internal Combustion Engine	300-650
Reciprocating Engines	250- 400
Furnaces of Heat treatment	375 – 700
Ovens of Dry Baking	230 – 600
Catalytic Convertors	400 – 700
Annealing	375 – 750

Table 2.2 Medium Temperature Range.

Various sources of waste heat at low temperature ranges are listed:

Sources of Waste Heat	**Temperature Range (^{o}C)**
Steam condensate processed	50-95
Condensate:	
Doors in Furnaces	30-50
Bearings	30-80
Welding Units	30-90
Molding Units (Injection)	35-90
Annealing Plants	70-250
Dies used in forming	30-90
Air Compressing units	30-60

Table 2.3 Low Temperature Range

2.4.2 Waste HeatRecovery:

Waste heat recovery involves re-utilization, processing and capturing of heat being let out which can enable generation of power (mechanical, electrical etc.).

These technologies lower the functional cost resulting in power generation.These technologies are still in growing stage and being proven theoretically. Also, many applications where there is a loss of heat unable to be recovered due to few barriers is still a problem.

A wide-rangingstudy of heat losses, recovery and barriers needed to research various opportunities and technologies are required. All these studies may lead in promoting energyefficiency.

Table 2.4 Recovery of Waste Heat Sources and their applications

Sources and End Uses of Waste Heat recovered	Applications
❖ Emissions from combustion: ✓ Glass smelting, ✓ Cementburner, ✓ Boiler. ❖ Heat from processes: ✓ Arc furnace, (Steel) ✓ Reverberatoryfurnace, ❖ Cooling water: ✓ Air compressors, ✓ I.C Engine. ❖ Losses via modes of heat transfer: ✓ Conduction, ✓ Convection, ✓ Radiation.	❖ Airpreheating via Combusted heat. ❖ Feed waterin boiler being preheated. ❖ Energy Generation. ❖ Steam used for generation of energy instead of mechanical work. ❖ Application of Heat exchanger broadly for phase changes in a cycle. ❖ In extreme weathers for localized cooling or heating the space.

2.4.3 Factors showing feasibility of Waste Heat Recovery:

Waste heat recovery Feasibility can be Assessed by segregating source and the sink were in the waste heat is fed. Main Constraintsof Waste heatinclude:

- ✓ Amount of Heat,
- ✓ Temperature of source,
- ✓ Contents,
- ✓ Plans of Operation schedule, and other statistics.

The above saidlimitations provide an amount of stream quantity which allows design limitations. The probabilities to govern waste heat recovery are delivered below:

2.4.4 Heatquantity:

The amount of heat is the measurement of quantity of power/energy within the waste heat source and on the other hand its quality can also be scaled by analyzing how much waste heat can be utilized and reused. Amount of waste heat trapped from the source depends upon temperature and the mass flow rate [11].

$$E = mh(t)$$

Here,

- E = Heat loss (Btu/hr),
- m = mass flow rate (lb/hr)
- h(t) = specific enthalpy (Btu/lb).

All the said parameters are in accordance to waste heat recovered.

2.4.5 Measuring temperature of Waste heat:

The temperature of the waste heat plays a vital role in higher probability of recovering waste heat. The range of such temperatures broadly vary in the range of cooler body at 35-90°C and hot body having temperature around 1,230°C. To obtain a healthy recovery of waste heat which enables proper heat transfer across, the source temperature must be more than the sink temperature. The gradient of temperature indicates the quantity as well as the quality of waste heat [13]. Few areas depending upon the temperature gradient are:

a) Heat transfer rate per unit surface area of heat exchanger.
b) Theoretical thermal efficiency.
c) Material of Heat Exchangers.

The recovery of waste heat potential is classified based on the temperature ranges as stated below:

- ✓ High: above 649ºC
- ✓ Medium: 230-650ºC
- ✓ Low: lesser than 230ºC.

2.4.6 Temperature&Selection of Material:

The choice of materials in construction of heat exchangers is very much important due to its ramification effect upon temperature.Unwanted chemical reactions may arise due to the increase in temperature dramatically.Equipment's of heat recovery may rapidly damage due to corrosive sources present in extracted waste heat

2.4.7 Composition of waste heat:

As chemical proportions cannot lonely control quality/quantity of the waste heat, composition of waste heat stream disturbs the recovery process as well as materials. Proportion & state of waste heat will govern thermal conductivity, heat capacity, and such types of features that have a serious impact on effectiveness. Also, the makeup of gases impacts heavily upon the design of heat exchanger, cost and preferred material.

Various Phases considered	Coefficient of Heat Transfer (W/(m^2-°K)
Water	5000-10000
Liquid organics	1500-2000
Gas @ 1MPa	250-400
Gas @ 1002 MPa	80-120

Allowable minimumtemperature:

Since temperature plays a vital role in many aspects. Thus, there is also a need to limit temperature range. Temperature is also linked with emergence of corrosion.Based upon the ingredients like flue gases, fuel, etc, like CO_2, H_2O (gaseous), various materials cause fouling. At temperatures below dew point condensation initiates and leads to deposition of many substances on surface walls cause fouling.

Figure 2.8Recuperator from Aluminum Furnace

2. Waste Heat RecoverySystems

3.1 Recuperator:

These devices extract waste heat from gases at various temperatures in applications such as incinerators, furnaces, ovens, burners, etc, under various modes of heat transfer. Based upon the modes of heat transfer the recuperators are defined by working principles as follows:

- ✓ Recuperator with radiation mode comprises of two concentric pipes geometrically. Here the warm waste gases pass through the inner most pipe and it heats the wall of pipe which further radiates to the cooler air sent inside through outer pipe. Because of radiation the air is preheated before sent in to furnace.
- ✓ In Recuperator with convection mode, these setups have a set of tubes of smaller diameters enclosed inside a shell. The warm waste gases are passed through the small tubes and the fresh cooler air being passed across the shell comprising of baffles within by convection carry the heat of waste gases performing preheating process.
- ✓ Recuperators with combined radiation/convection mode are also available. These assemblies have a radiation section trailed by convection section inbuilt within the recuperator to witness maximum effectiveness.

Materials generally used in construction of recuperators are metallic orceramic. Generally, for temperatures below1100ºC use metallic recuperators while above 1100ºC use ceramic materials [13] [14].

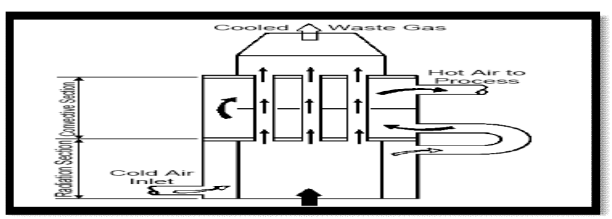


Figure 3.1 Combined Radiation/Convection Recuperator

3.2 Regenerator:

Regenerator is also basically a furnace. Regenerative furnaces are constructed with two brick chambers. Inside these chambers air circulates alternatively i.e. hot and cold currents. Here there are different chambers through which gases circulate and the wall bricks of chamber absorb the heat from the gases resulting in rise of temperature.

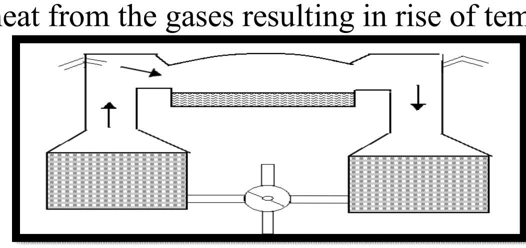


Figure 3.2 RegenerativeFurnaceDiagram

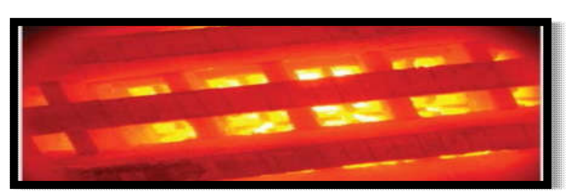


Figure 3.3 Checker Work inGlass

3.3 Rotary Regenerator:

Rotary regenerators are enabled with a porous membrane to enable storage of heat by allowing alternating hot and cold gas flow inside the generator. These generators have air preheaters with help of rotating porous disc across parallelly placed channels, one channel for hot gas whereas other for cooler one.

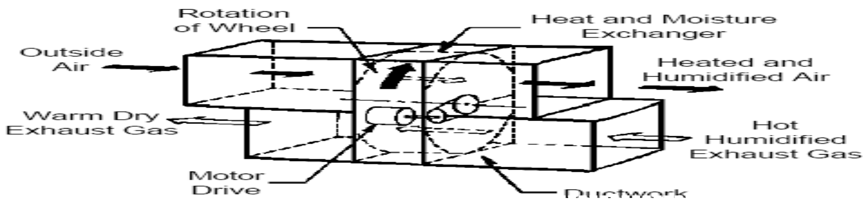


Fig 3.4 Rotary Regenerator

Figure 3.5 Rotary Regenerator on a Melting Furnace

3.4 Passive AirPreheaters:

These are the devices used for the cause of heat recovery in gaseous medium at medium temperature applications. Using this device, the drawback of precipitate contamination too is lowered in the streams.These are generally deployed in Gas turbines, boilers, furnaces and various other recovery devices. Passive preheaters are classified as: a)Plate type; b) Heat pipe.

In the plate type,several parallel plates are placed which formdistinct channels containing hot & cool gas torrents.

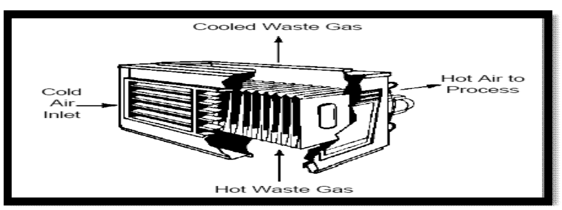


Figure 3.6 Passive Gas to Gas Air Preheater

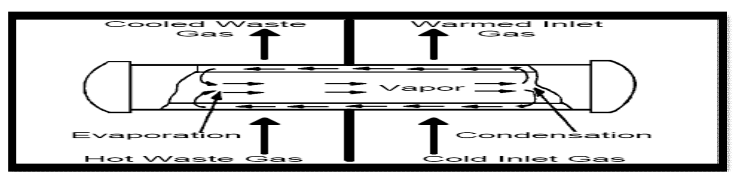


Figure 3.7 Heat Pipe Heat Exchanger

3. WASTEHEAT RECOVERY BENEFITS:

Waste Heat Recovery benefits are categorizedgenerally in two classes:

4.1 DirectBenefits:

The result required is efficiency of process. The efficiency can be directly enhanced by recovering waste heat in a substantial amount. Moreover, cost of processing along with utility consumption reduces. The more the heat being recovered the more will be the efficiency and the lesser will be the cost.

4.2 IndirectBenefits:

- Pollution:There is a reduction in pollution scale. Numerous gases such as carbon monoxide gas, carbon disulphate, carbon sooth, trichloroethylene, Butadiene and other plastic chemicals etc, which are also toxic if releasedinto atmosphere.On the other hand, if these are treated in the incinerators they provide dual outcomes that is it recovers heatas well as lowers environmental pollutiongrade.

- Reducing Equipment Dimensions: With the idea of recovering waste heat it promotes the way of fuel economy, which in return paves path in reduced flue gases being generated. Thus, due to less gases being generated the need of flue gases management equipment's reduces. So, the dimensions of these equipment reduce, resulting in compact modules.

4. THERMOELECTRICGENERATORS

5.1 Introduction:

The phenomenon of Thermoelectric by the name itself describes the production of electrical power generated due to the temperature difference maintained across.These generators are also named as Seebeck generators as they work upon the Seebeck principle.A German named Thomas Johann Seebeck was the innovator of this generator [15].

5.2 SeebeckEffect:

This principle states that when two junctions of a thermal conductor are maintained at different temperatures, there emerges an electron jump from hot junction to cold junction of thermal velocities. Seebeck the scientist found out that when a metal conducting material's one end is kept on hot side and the other end is kept on cold side an EMF is generated across these ends.

Seebeck investigated by making basic connections at junctions of different materials and

$$V = S*T_{12}$$

Here; V=EMF produced across the junctions;
S=Seebeck Coefficient;
T_{12}=Temperature Gradient across the junctions.

The Seebeck coefficient of circuit can be obtained by following the shown line diagram. In this the Wire-A ends are connected to wire-B ends but the wire-B is interrupted with a voltmeter.

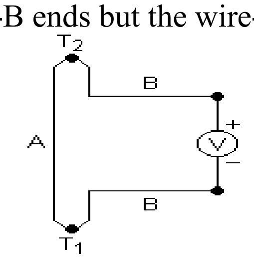


Figure 5.1 Measurement of Seebeck Coefficient

5.3 WorkingPrinciple:

Two thermo electric semiconductors each of N-type and P-type are present inside the thermoelectric generator under the temperature gradient connected in series electrically sandwiched by conducting plates

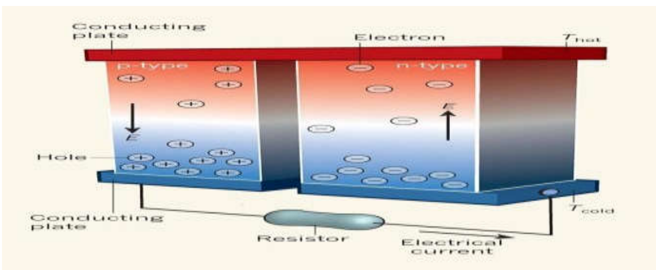


Figure 5.2 Thermoelectric Generator Working

Thermoelectric Power Generation

The voltage and the temperature gradient are in proportionality directly to each other with a constant i.e. Seebeck coefficient.

$$V = \alpha \Delta T.$$

A healthy thermoelectric material has the coefficient (Seebeck) in the range 100 µV/K-300 µV/K. So to form a thermoelectric device many thermoelectric couples are required to be connected in series resulting in voltage generation.

5.4 Design factor forTEG:

The size of heat exchanger which can absorb heat on source and reject it towards sink depends that how much heat is being focused through this. Heat exchangers are generally larger than TEG's since high power to voltage ratio is required. Thus, when size is larger power production overtakes efficiency. Even tough the temperature gradient may be less.

5.5 Figure-of- Merit(ZT):

Figure of Merit is the efficiency of thermoelectric which relies upon temperature gradient($\Delta T = Th - Tc$). Like other devices, thermoelectric generators also cannot have efficiency higher than Carnot cycle. The Figure of Merit is given by:

$$h = \frac{\Delta T}{T_h} \cdot \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + T_c/T_h}$$

Here;

The initial term is the carnot efficiency and the figure of merit for the device is given by:

$Z = \alpha^2 \sigma / \lambda$

α =Seebeck coefficient

σ =electrical conductivity

λ =conductivity

Z depends upon the degree of temperature, Figure of merit is the multiple Z.T which is the dimensionless number. The T used in figure of merit is the average operating temperature. This dimensionless parameter represents the maximum power efficiency [16].

5.5.1 MaximumZT:

Since theoretical value of Z has no prescribed range so therefore ZT value is also unknow and becomes a bit difficult to obtain high ZT in regard of electrical & thermal conductivity of materials. To lower the resistance heating affect in the thermo electric devices large electrical conductivity is required and on other side lesser thermal conductivity is required to achieve higher temperaturedifference across

5.5.2 Efficiency, ZT and TemperatureDifference:

It is very essential to know that many Thermoelectricplants rely upon temperature; it is not lonely the operating temperature difference, but also the real temperature. Thermoelectricunits are useful to produce DC(direct current) power upon an existing temperature difference.

The max efficiency of a Thermoelectric unit can be obtained by following calculations:

$$\eta_{\max} = \left[\frac{T_h - T_c}{T_h}\right] \cdot \left[\frac{\left(1+Z^*\overline{T}\right)^{1/2} - 1}{\left(1+Z^*\overline{T}\right)^{1/2} + 1}\right]$$

Here Z* =Optimum Z of semiconductor couple inside a Thermoelectricunit,

- *Th,Tc* = Hot and Cold junction temperatures.

- T = Average of Th, Tc.

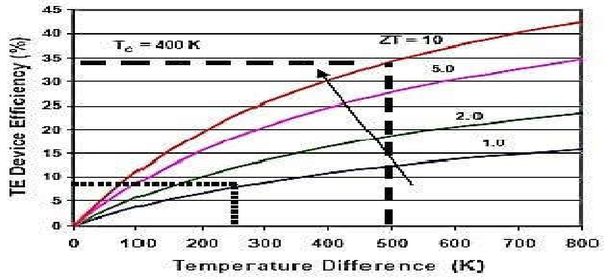


Figure 5.3 Efficiency vs Temperature Difference

5.6 Thermoelectric GeneratorsAssemblies:

Thermoelectric generatorsetups comprise of several hundred arrays of (P-N) type thermocouples merged together electrically in series whereas parallel thermally.These devices are generally homogeneous in generation of certain power.

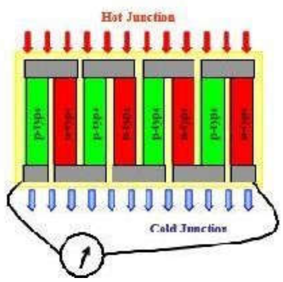


Figure 5.4 Multi-elementthermoelectricdevice Figure 5.5 ThermoelectricModule

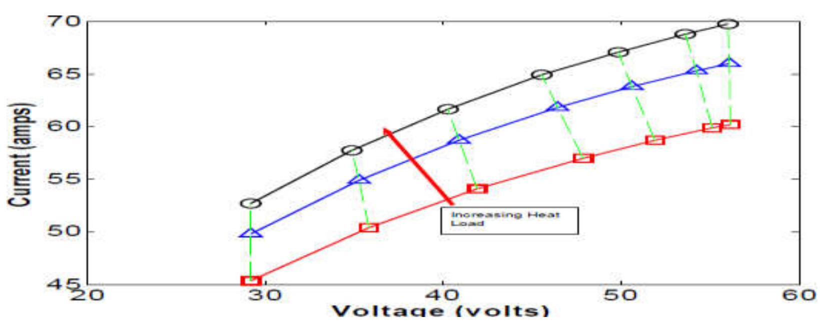


Figure 5.6 Current vs Voltage for Thermoelectric Generator

5.7 Advantages of TEG over conventional heatengines:

In contrast to the traditional heat engines, TEG marks the absence of moving parts and abstain from making noises.These generators have been serving the purpose reliably for past 30 years. These are operationally maintenance-free, applicableas space probes in comparison to large ones especially inconventional heat engines and TEGs are oflesser efficiency.

5.8 Applications ofTEG:

There are plenty of fields were Thermoelectric generators are applied.Often, TEG's are applied in low power uses. In heavy and bulky setups like Stirling engines this is not possible

- Practice of TEG's up on gas pipelines is a common application.Noted example of this is deploying them on pipelines to consume power upto 5kW.
- In unmanned regions TEG's are applied as off-grid energy generators. There is no situation

of breakdown or shutoff since these are free of moving parts.

5.9 Limitations:

Apart from the main limitations of lesser efficiency, high initialinvestments, there exists two matters of concerns listed below:

- **High output resistance** –To attain a noteworthy output there is a need of large seebeck coefficient required.A basic way to meet this requirement is to connect several thermoelectric units in series, resulting in effective output resistance generally above 10Ω. Power is only utilized effectively under large resistances, or else it is wasted across output resistance. This can be rectified in devices by rearranging the connections rather than conventional series connections.
- **Adverse thermal characteristics** –Due to less conductivity (thermal) required inhealthy TEG's, the adverse characteristics can reduce the dissipation of heat in devices. These are beneficial economically only for small powers under temperature greater than 200°C [18,19].

5. THERMOELECTRICCOOLING

6.1 Introduction:

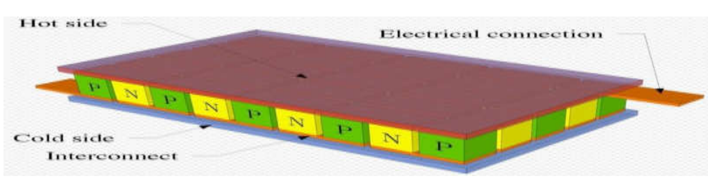
Thermoelectric cooling is a phenomenon based on the principle of Peltier. Peltier effect states that a heat flux is generated upon application of voltage across junctions of various materials. When the voltage is applied on the thermoelectric cooler across the junctions, then heat is absorbed at one end and heat is formed at other.This cooler is also known as Peltier cooler,

Figure 6.1 Operation of TEC

6.2 Operating principle:

The main principle of operation for thermoelectric coolers isPeltier effect also known as thermoelectric effect. These two-sided devices when applied with DC current through it transfers heat from one side to opposite side resulting that both sides are at different temperatures i.e. one cooler than the other. A heat sink is placed at hotter side to maintain a temperature whereas the other side may also drop in temperature below room temperature [16].

Figure 6.2 Thermoelectric Cooler Schematic



6.3 Construction:

A set of two distinct semiconductors one of N-type and other P-type are assembled together as it requires semiconductor combination of unlike electron densities.

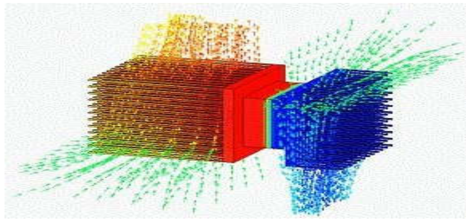


Figure 6.3 Free Convection in a TEC

In above figure convection effect upon the thermoelectric cooler added with heat sink is being displayed with surface temperature contours on both sides in the shape of trajectories.

Figure 6.4 Peltier Device

6.4 Performance:

Thermoelectric cooler generally produces a temperature difference of 70°C across the hot and cold ends. Larger the heat transferred with help of Thermoelectric coolers, the lesser is the efficiency, as Thermoelectric coolers dissipate heat transferred and generates heat via the powerconsumed. The heat consumed is proportional to product of current and time.

Here P = Peltier Coefficient,

I = current,

$$W = PIt$$

t = time.

Peltier Coefficient relies upon temperature as well as material used in Thermoelectric cooler.These TEC's are 4 times less efficient in refrigeration when compared to conventional means i.e. compression cycle. Due tolower efficiency, thermoelectriccoolers are used in environments.

6.5 Thermoelectric Heating andCooling:

eltier effect states that when current is flown through a circuit involving the two dissimilar material conductors there develops a temperature difference at the junctions as per the current being passed resulting in thermoelectric cooling or heating. JeanPeltier discovered Peltier effect in 1834, later in 1838 this effect was expanded by physicist Emil Lenz.

6.6 Advantages:

8.1.1 Simple
8.1.2 Noiseless
8.1.3 Compact
8.1.4 Lightweight
8.1.5 Eco friendly since no refrigerants areused.
8.1.6 More reliable than systems with movingparts

8.1.7 Easy control by varyingcurrent
8.1.8 Used for dehumidifying air for medicalindustry

6.7 Disadvantages:

- Efficiency of thermo-electric cooling isless.
- 5–10% efficiency as compared with that of ideal reversed CarnotCycle
- 40–60% COP as compared to conventional compression refrigerationcycle

6.8 Applications:

- Consumer products comprises of Peltier elements within them like camping, portable coolers, electronic components.
- Dehumidifiers used to extract water from air using Peltier heat pumps resulting in the cooling effect.

6. PROBLEM DEFINATION OF PROJECT

Generate power by recovering waste heat by carrying out study and evaluate the performance of the system using thermoelectric generator (TEG).

Assumptions and considerations:

- Total of six (6) Thermo Electric Generator module areused.
- The thermopile is in seriesarrangement.
- Hot plate is heated up to 300^{o}C.
- Cold plate is cooled up to 5^{o}C.
- The cold and hot junctions of generator are completely in contact with the hot plate and coolingtank.
- Cold side temperature is kept constant during performance analysis, and hot sideis varied.

Decent Thermo electric materials show case certain characteristics as listed below:

7. CONSTRUCTION OF MAINCOMPONENTS

The following components had been machined, fabricated and assembled in order tobe arranged as experimental setup. These three components have been chosen by virtue of the effort and time consumed in their fabrication. They are:

1. HeatExchanger
2. HotPlate
3. Cooling WaterTank

   The step by step construction details for each of the following part is illustrated by beans of 3-D drawings using Solids Works 2008 Software.

8.1 HeatExchanger:

The heat exchanger is a device whichfacilitatestransference of heat from the cold junction of the Thermo Electric Generator at a faster rate. This is done by placing the heat exchanger in thermal contact with the cold Thermo Electric Generator side and allowing water (cooled) to pass through it, thereby decreasing the temperature of junction.

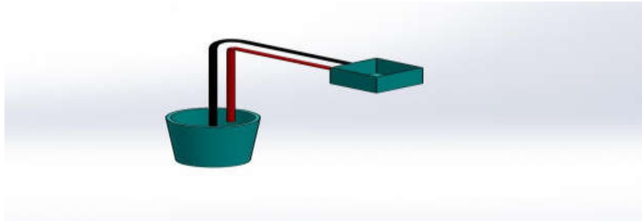


Figure 8.1 Heat exchanger

8.2 HotPlate:

The hot plate is a circular shaped plate that is placed on the heater. Over this plate the Thermo Electric Generators are placed over which the heat exchanger is securely fixed with the help of thermal conducting paste. The hot plate is also made of aluminum. Provision was made for determination of temperatures at the mid-section and top surface of the plate by drilling of radial holes at mid plane and machining grooves on top surface of the plate respectively.

The various operations performed on the plate are:

a) A circular groove was machined on the lower surface of the plate to enable secure placing of the hot plate over the heater coils.
b) The series of Six (6) thermoelectric generators were placed on top of this arrangement.
c) This was again followed by a layer of thermal conducting paste.
d) Finally this entire sub-assembly was attached with the heat exchanger assembly.

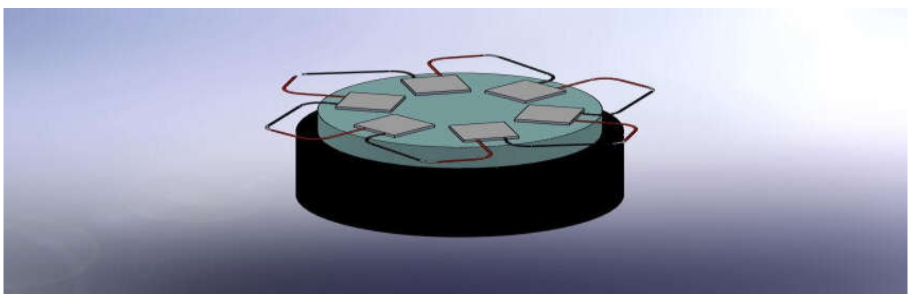


Figure 8.2 Hot Plate

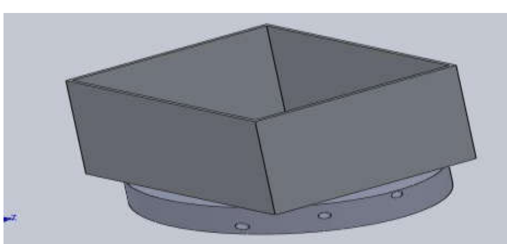


Figure 8.3 PlateHeatExchanger Figure 8.4 Finished workpiece

8.3 Cooling Water tank

The cooling water tank enables higher power being produced by the Thermo Electric Generator, by facilitating further reduction of temperature on coolerface of the TEG.

The fabrication of the cooling tank was carried out by following steps:

a) A rectangular aluminum tank of dimensions 170mm x 170mm x 80mmwas taken and machined on all surfaces to produce a smoothfinish.

b) Holes of diameter 10mm was drilled at oneend.

c) Water circulation is done in the cooling tank as to maintain low temperature on thecold side of module such that more temperature isabsorbed.

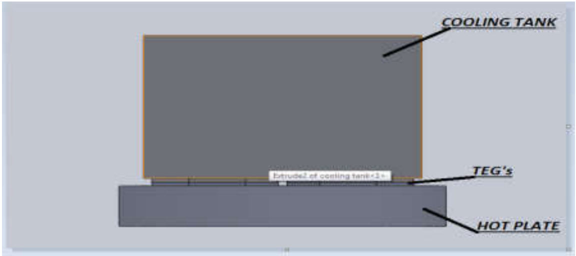


Figure 8.5 Front view in SolidWorks

9. COMPONENTS OF SETUP

The following are the main components used in the experimental setup. In our entire setup hot plate was used as a source were as heat exchanger as a sink. All componentis described briefly below with its functional role in the setup.

1. Water coolingtank
2. Heatexchanger
3. Hotplate
4. Heater
5. Thermocouples
6. Variable powersupply
7. Computer with EVB LoggerSoftware
8. Output measurement and displaysetup
9. Multimeter

9.1 Water CoolingTank:

The water-cooling tank provides water to the cold junction of the Thermo Electric Generator passing through the heat exchanger. The rectangular aluminum tank of dimensions 170x170x80 mm was used as cooling water tank. The volume of water was equivalent to 2.3 litres.The bottom of the cooling tank is placed in contact with the help of thermal conducting paste to the cold junction of Thermo Electric Generator’s. The water from the source container is replaced periodically with fresh cold water for the continuous use during the observations. Water in the bucket has to be stirred from time to time in order to prevent local concentration of heat. The water thus cooled is transported to the heat exchanger using pipes.

Figure 9.1 View of a Cooling tank

9.2 HeatExchanger:

The heat exchanger is a device that allows the transfer of heat at the cold junction ofthe thermoelectric generator, from the Thermo Electric Generator surface (hot) to the cooling fluid (cold

Figure 9.2 Heat Exchanger on top of Hot Plate

9.3 Hot plate:

The hot plate provides the interface between the hot coils of the heater and the thermoelectric generators. It is a circular plate made of aluminum. The circular groove at the bottom enables good positioning of the plate on the coils and prevents slipping and falling. Radial holes are madeatfew pointsalongthecircumferencetoallowthemeasurementoftemperaturesat those section.

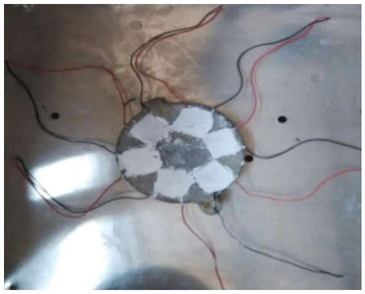


Figure 9.3 Thermo ElectricGenerator arranged in series

9.4 Heater:

The heater is used to produce the hot temperatures required to produce the electricity in the thermoelectric generator. The heater is connected to variable power supply to vary the hot plate temperature. The power rating of the Heater is 1500 Watts.

Figure 9.4 Heater

9.5 Thermocouples:

The thermocouples used to measure the temperatures are connected to an electronic display. There is a total of six (6) thermocouples used. The electronic display allows either the reading of a single thermocouple to be viewed or keeps changing through the various thermocouples in thesystem.

9.6 Variable PowerSupply:

The power supplied to the heater first passes through the variac which varies the supply of power to heater. This in turn allows for the control of heater temperature. The voltage can be varied from 0-240V, while the current varies from 0-5A. The maximum voltage chosen was around 200V to ensure safety of equipment. The temperature reached at this point was nearly 650^{o}C at the heater coil location.

Figure 9.5 Variable Power Supply to Heater and Thermocouples with Digital Readings

9.7 Output Measurement and DisplaySetup:

The output power of the thermoelectric generator is used to light up electric circuit consisting of three (3) LED bulbs acting as loads. The bulbs are connected with electronic displays for voltmeter and ammeter readings. A separate thermocouple is also provided along with its own display. The bulbs can be switched on or off using the switch to light up either a single bulb or all bulbssimultaneously.

Figure 9.6 Display Setup of Voltmeter & Ammeter

9.8 Multimeter:

In order to measure the voltage or current at any desired site, a Multimeter was used. It also helps in verification of values obtained in the standard voltmeters and ammeters. It can be used to measure voltage up to 1000V dc and 750V ac. The current measuring capacity of the Multimeter is up to 10Amps.

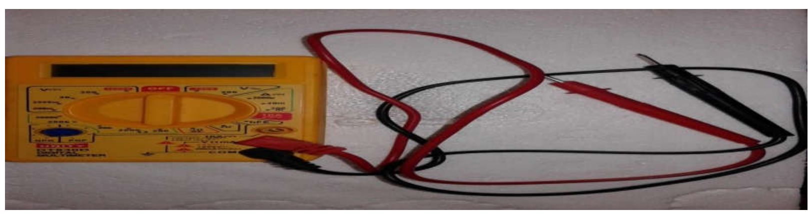


Figure 9.7 Multimeter

9.9 (TEG) Thermoelectric-Generator:

TEG is the essential device based on principal of See-beck effect which convertswaste heat into useful electrical energy. Specifications of the TEG are:

9.9.1 Max. Temperature:300 ^{O}C	**TEC1-12706**
9.9.2 RatedPower:5.1W	-TE: - Thermoelectric
9.9.3 RatedVoltage:3V	-C: - Standardsize
9.9.4 RatedCurrent:1.66A	-1: -One stage Thermoelectricmodule.
9.9.5 Open CircuitVoltage:10.8V	-127: -These are the number of P-Ncouples
9.9.6 Resistance (at 200^{O}C):1.86ohm	-09: -Rating Current ,9Amperes.
9.9.7 Area: 40mm x40mm	
9.9.8 Thickness:3mm	

Figure 9.8 Thermo Electric Generator Module

Input measuring unit

Figure 9.9 Complete Setup Arrangement

10. EXPERIMENTATION PROCEDURE

1) Connect the electrical circuit to the output of Thermo Electric Generator modules inseries.
2) Place the hot plate assembly on theheater.
3) Insert the thermocouples at appropriate locations for temper Output measuring unit ment.
4) Switch on the heater and vary the input voltage to required value using arheostat.
5) Switch on the pump and let the cooling tank fill with coldwater.
6) Connect the thermocouple ends to the points where temperature is to befound.
7) Allow cooled water to flow through the heatexchanger.

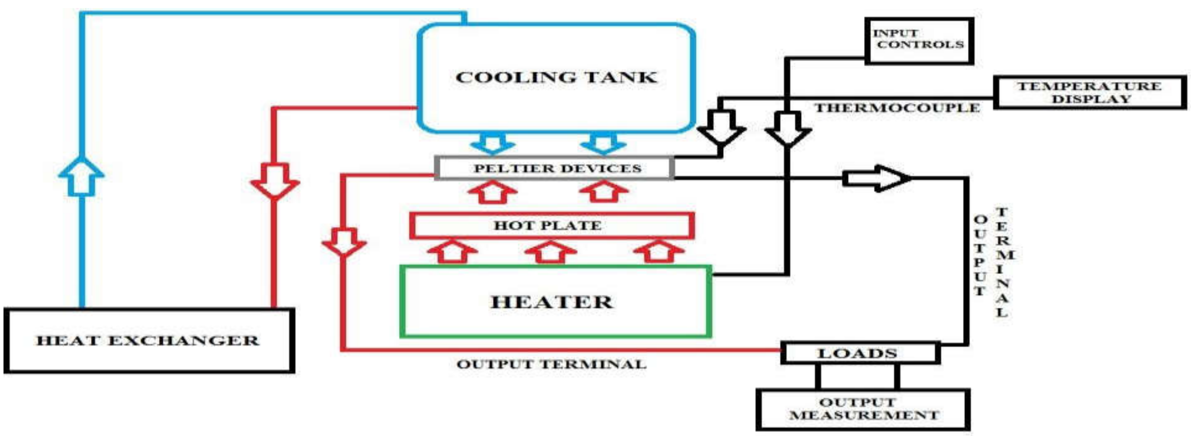


Figure 10. Line diagram of setup

After noting down values of the various variables involved, different graphs were plotted against the temperatures. The various graphs include:

1. Power consumed vsTemperature
2. Output voltage vsTemperature

11. RESULTS

Tables:

11.1Observation Table for 1 Watt LEDBulb:

Time (am)	Voltage V_c volts	Current I_c amps	Load Watt watts	Voltage V_o volts	Power V_c XI_c watts	Temp of Hotplate T_h	Temp of Coldtank T_c	Ambient Temp T_{amb}	Temp Difference ΔT
9:06	2.25	0.009	1	2.42	0.0202	30	11	35	19
9:09	3.30	0.039	1	4.46	0.1287	33	11	35	22
9:12	4.50	0.076	1	6.56	0.342	45	14	36	31
9:14	5.40	0.111	1	8.7	0.5994	49	14	36	35
9:16	6.02	0.132	1	10.3	0.7946	55	15	36	40
9:18	6.60	0.165	1	12	1.089	60	15	36	45
9:20	7.60	0.193	1	13.6	1.4668	70	15	36	55
9:22	8.40	0.215	1	15.06	1.806	75	15	36	60
9:24	8.90	0.237	1	17	2.1093	81	15	36	66
9:25	9.20	0.251	1	17.8	2.3092	86	15	36	71
9:26	9.60	0.258	1	18.3	2.4768	90	15	36	75
9:27	9.74	0.264	1	18.6	2.5713	92	17	36	75
9:28	9.90	0.267	1	18.9	2.6433	98	17	36	81
9:29	10.06	0.274	1	19.3	2.7564	102	19	36	83
9:30	9.60	0.26	1	19.5	2.496	108	19	36	89
9:31	10.16	0.282	1	19.97	2.865	116	22	36	94
9:33	10.33	0.287	1	20.23	2.964	120	23	36	97
9:35	10.44	0.291	1	21.3	3.038	129	24	36	105
9:36	10.48	0.30	1	21.43	3.144	140	24	36	116
9:38	11.21	0.322	1	22.6	3.609	142	28	36	118
9:39	11.65	0.33	1	23	3.844	163	28	36	135
9:40	12	0.348	1	24.8	4.176	177	29	36	148

The tabular column shows the various readings of the temperatures measured through the thermocouples positioned at the top of the plate, bottom of cooling tank and ambient atmosphere. Change in temperature affects the characteristics of the thermoelectric generator module. The parameters measured against the temperature variation are the voltages (V) - open and closed circuit, current (I) and power (W).

The values were taken for the first load (1W) LED bulb, during the experimentation.

11.2Observation Table for 5 Watts LEDBulb:

Time	Voltage V_c volts	Current I_c amps	Load Watt watts	Voltage V_o volts	Power V_c XI_c watts	Temp of Hotplate T_h	Temp of Coldtank T_c	Ambient Temp T_{amb}	Temp Difference ΔT
9:16	5.79	0.162	5	10.3	0.937	55	15	36	40
9:18	5.9	0.210	5	12	1.239	60	15	36	45
9:20	5.9	0.246	5	13.6	1.451	70	15	36	55
9:22	6	0.298	5	15.06	1.788	75	15	36	60
9:24	6.07	0.33	5	17	2.003	81	15	36	66
9:25	6.03	0.355	5	17.8	2.140	86	15	36	71
9:26	6.1	0.381	5	18.3	2.324	90	15	36	75
9:27	6.2	0.376	5	18.6	2.331	92	17	36	75
9:28	6.05	0.380	5	18.9	2.299	98	17	36	81
9:29	6.11	0.384	5	19.3	2.346	102	19	36	83
9:30	6.11	0.4	5	19.5	2.444	108	19	36	89
9:31	6.10	0.410	5	19.97	2.501	116	22	36	94
9:33	6.04	0.399	5	20.23	2.409	120	23	36	97
9:35	6.10	0.419	5	21.3	2.556	129	24	36	105
9:36	6.09	0.430	5	21.43	2.618	140	24	36	116
9:38	6.16	0.46	5	22.6	2.833	142	28	36	118
9:39	6.14	0.478	5	23	2.934	163	28	37	135
9:40	6.20	0.515	5	24.8	3.193	177	29	37	148

The tabular column shows the various readings of the temperatures measured through the thermocouples positioned at the top of the plate, bottom of cooling tank and ambient atmosphere. Change in temperature affects the characteristics of the thermoelectric generator module. The parameters measured against the temperature variation are the voltages (V) - open and closed circuit, current (I) and power (W).

The values were taken for the first load (5W) LED bulb, during the experimentation.

11.3Observation Table for 10 Watts LEDBulb:

Time	Voltage V_c volts	Current I_c amps	Load Watt watts	Voltage V_o volts	Power V_c XI_c watts	Temp of Hotplate T_h	Temp of Coldtank T_c	Ambient Temp T_{amb}	Temp Difference ΔT
9:18	5.92	0.205	10	12	1.213	60	15	36	45
9:20	4.7	0.30	10	13.6	1.41	70	15	36	55
9:22	3.7	0.38	10	15.06	1.406	75	15	36	60
9:24	3.3	0.432	10	17	1.425	81	15	36	66
9:25	3.05	0.455	10	17.8	1.387	86	15	36	71
9:26	2.88	0.468	10	18.3	1.347	90	15	36	75
9:27	2.8	0.477	10	18.6	1.3356	92	17	36	75

9:28	2.76	0.486	10	18.9	1.341	98	17	36	81
9:29	2.67	0.475	10	19.3	1.268	102	19	36	83
9:30	2.77	0.512	10	19.5	1.418	108	19	36	89
9:31	2.47	0.522	10	19.97	1.289	116	22	36	94
9:33	2.41	0.572	10	20.23	1.233	120	23	36	97
9:35	2.39	0.541	10	21.3	1.292	129	24	36	105
9:36	2.45	0.552	10	21.43	1.352	140	24	36	116
9:38	2.43	0.572	10	22.6	1.389	142	28	36	118
9:39	2.45	0.599	10	23	1.467	163	28	37	135
9:40	2.47	0.62	10	24.8	1.531	177	29	37	148

The tabular column shows the various readings of the temperatures measured through the thermocouples positioned at the top of the plate, bottom of cooling tank and ambient atmosphere. Change in temperature affects the characteristics of the thermoelectric generator module. The parameters measured against the temperature variation are the voltages (V) - open and closed circuit, current (I) and power (W).

The values were taken for the first load (10 W) LED bulb, during the experimentation.

11.4Observation Table for 1 Watt, 5 Watts and 10 Watts LEDBulbs:

Time	Voltage V_c volts	Current I_c amps	Load Watt	Voltage V_o volts	Power V_c XI_c watts	Temp of Hotplate T_h	Temp of Coldtank T_c	Ambient Temp T_{amb}	Temp Difference ΔT
9:18	4.4	0.265	16	12	1.166	60	15	36	45
9:20	3.5	0.313	16	13.6	1.095	70	15	36	55
9:22	3.18	0.391	16	15.06	1.243	75	15	36	60
9:24	2.9	0.435	16	17	1.261	81	15	36	66
9:25	2.89	0.452	16	17.8	1.306	86	15	36	71
9:26	2.7	0.471	16	18.3	1.271	90	15	36	75
9:27	2.7	0.478	16	18.6	1.2906	92	17	36	75
9:28	2.68	0.481	16	18.9	1.289	98	17	36	81
9:29	2.56	0.470	16	19.3	1.203	102	19	36	83
9:30	2.65	0.515	16	19.5	1.364	108	19	36	89
9:31	2.32	0.506	16	19.97	1.173	116	22	36	94
9:33	2.35	0.511	16	20.23	1.200	120	23	36	97
9:35	2.34	0.527	16	21.3	1.233	129	24	36	105
9:36	2.3	0.54	16	21.43	1.242	140	24	36	116
9:38	2.33	0.577	16	22.6	1.344	142	28	36	118
9:39	2.37	0.573	16	23	1.358	163	28	37	135
9:40	5.95	0.512	16	24.8	3.046	177	29	37	148

The tabular column shows the various readings of the temperatures measured through the thermocouples positioned at the top of the plate, bottom of cooling tank and ambient atmosphere. Change in temperature affects the characteristics of the thermoelectric generator module. The parameters measured against the temperature variation are the voltages (V) - open and closed circuit, current (I) and power (W).

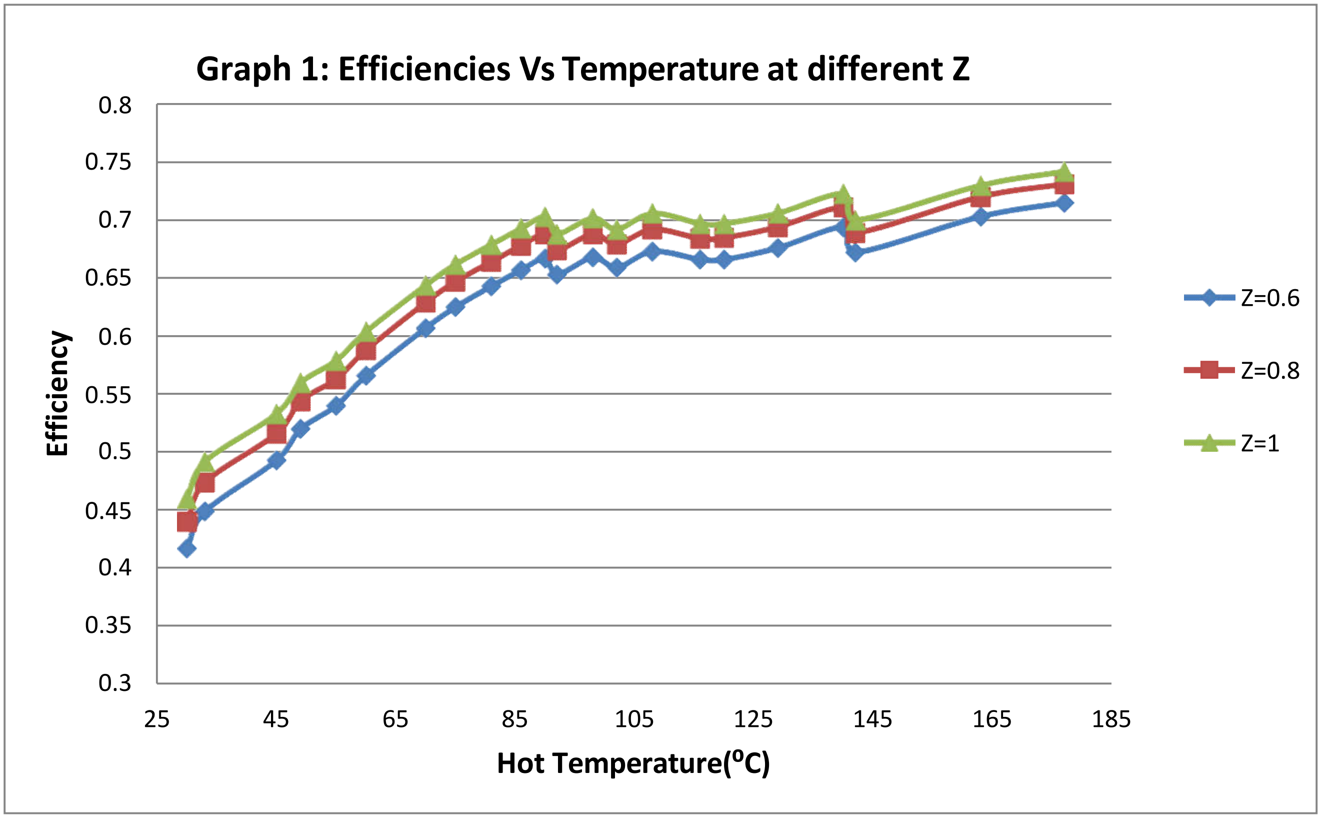
The values were taken for the first load (10 W) LED bulb, during the experimentation.
Efficiency at various values of Z=0.6,0.8,1:

Time	Temp of Hotplate T_h°C	Temp of Coldtank T_c°C	$\frac{Th}{Tc}$	$\frac{Th - Tc}{Th}$	$\frac{Th + Tc}{2}$	Efficiency At 0.6	Efficiency At0.8	Efficiency At 1
9:06	30	11	2.72	0.633	20.5	0.417	0.440	0.460
9:09	33	11	3	0.666	22	0.449	0.474	0.492
9:12	45	14	3.21	0.688	29.5	0.493	0.516	0.533
9:14	49	14	3.5	0.714	31.5	0.520	0.544	0.560
9:16	55	15	3.66	0.727	35	0.540	0.563	0.579
9:18	60	15	4	0.750	37.5	0.566	0.588	0.604
9:20	70	15	4.66	0.785	42.5	0.607	0.629	0.644
9:22	75	15	5	0.800	45	0.625	0.647	0.662
9:24	81	15	5.4	0.814	48	0.643	0.664	0.679
9:25	86	15	5.73	0.825	50.5	0.657	0.678	0.693
9:26	90	15	6	0.833	52.5	0.667	0.688	0.703
9:27	92	17	5.41	0.815	54.5	0.653	0.674	0.688
9:28	98	17	5.764	0.826	57.5	0.668	0.688	0.702
9:29	102	19	5.368	0.813	60.5	0.659	0.679	0.692
9:30	108	19	5.684	0.824	63.5	0.673	0.692	0.706
9:31	116	22	5.272	0.810	69	0.666	0.684	0.697
9:33	120	23	5.217	0.808	71.5	0.666	0.684	0.697
9:35	129	24	5.375	0.814	76.5	0.676	0.694	0.706
9:36	140	24	5.833	0.828	82	0.694	0.711	0.723
9:38	142	28	5.071	0.802	85	0.672	0.689	0.700
9:39	163	28	5.821	0.802	95.35	0.703	0.720	0.730
9:40	177	29	6.103	0.836	103	0.715	0.731	0.742

The above table show the values of efficiency with variation in temperature of thethermoelectric module setup. The value of Z is assumed as 0.6, 0.8 and 1 in the calculations. The efficiency was calculated using the followingformula:

$$h = \frac{\Delta T}{T_h} \cdot \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + T_c/T_h}$$

Where $\Delta T/T_h$= Carnot efficiency &ZT = figure of merit of device.



The Graphical observation shows that efficiency increases upon increasing the temperature gradient.

Upon observing the graph, we see that efficiency grows in proportion to figure of merit of thethermoelectric material. The figure of merit Z is given as:

$$Z = (\alpha^2\sigma)/\lambda$$

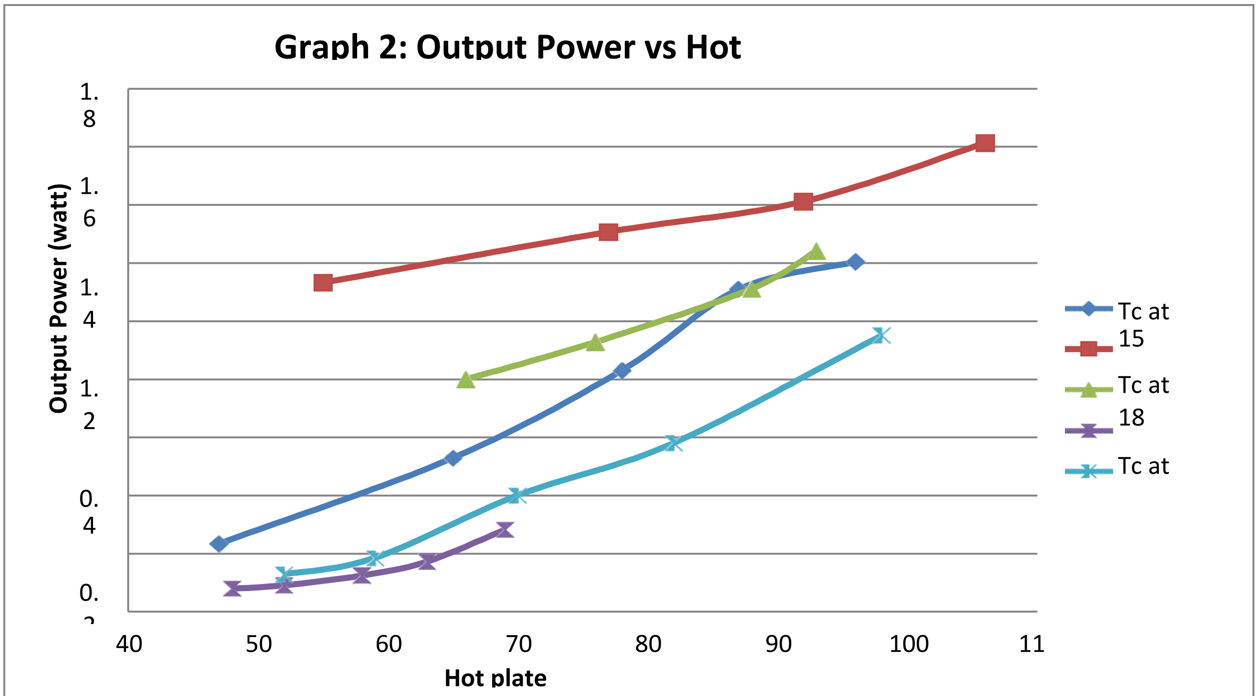
Where, α =Seebeck coefficient (volt-kelvin^{-1})

σ = electrical conductivity (ampere-volt^{-1}·meter^{-1})

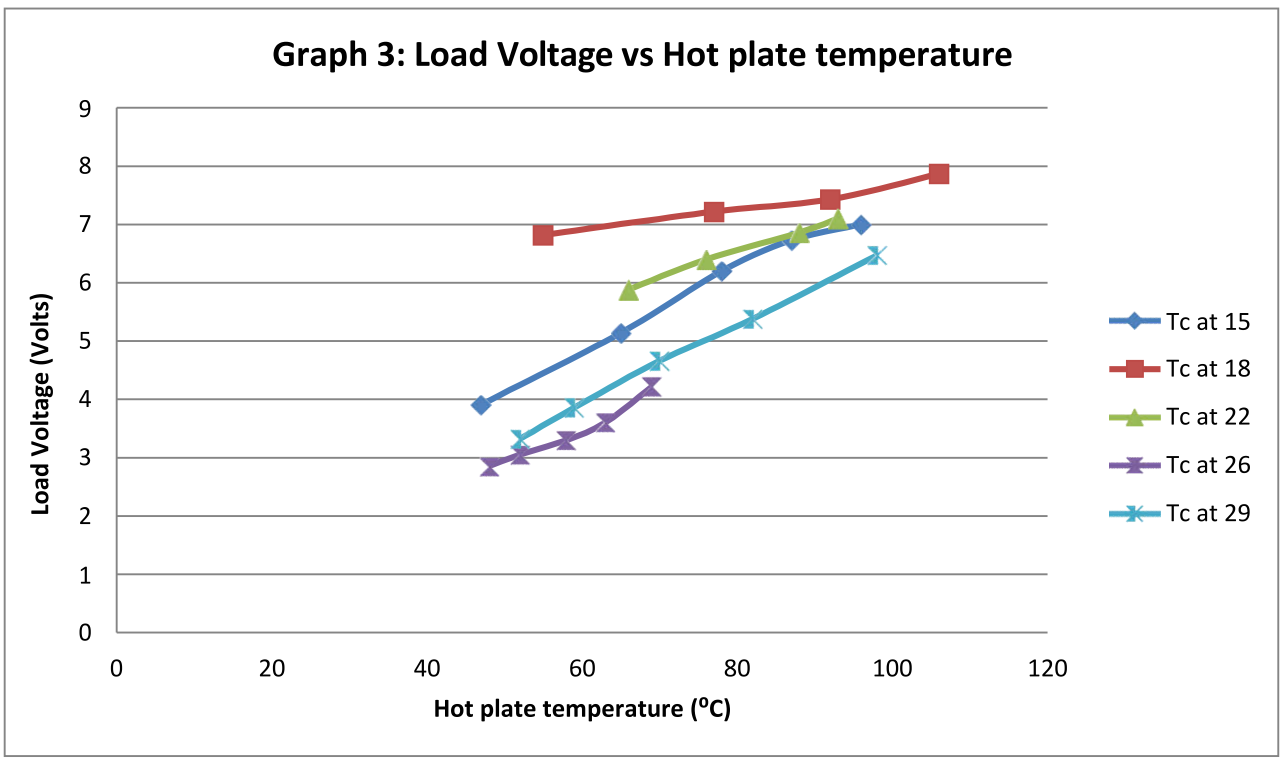
λ = thermal conductivity(watt-meter^{-1}·kelvin^{-1})

Here all theseα, σ,λ are the values of the material.

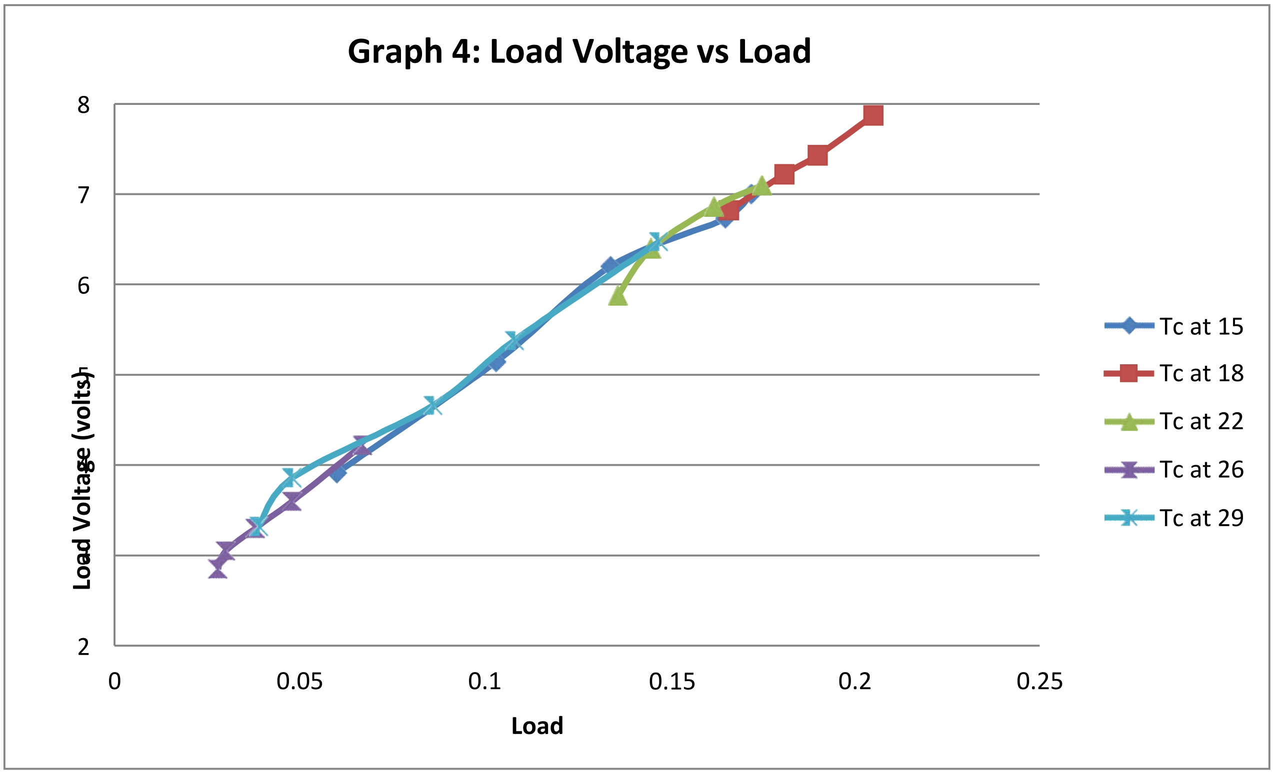
PERFORMANCE CHARACTERISTICS CURVES:



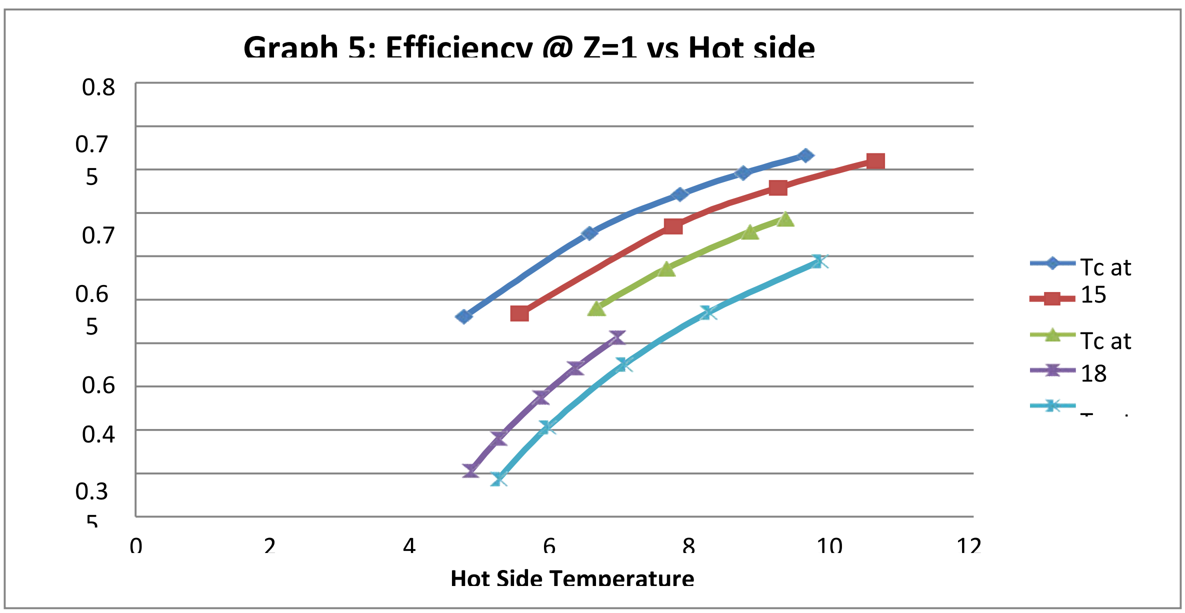
The Graphical observation shows that output power increases upon increasing the hot side temperature.



The Graphical observation shows that output voltage increases upon increasing the hot side temperature.



The Graphical observation shows that load voltage increases upon increasing the h.



The Graphical observation shows that efficiency increases upon increasing the hot side temperature.

12. CONCLUSION

An experimentation setup was developed to conduct a performance analysis of a thermoelectric generator (TEG). Our setup involves a thermoelectric generator module, across which the temperature difference is maintained by heat generated from an electric coil heater at the hot junction and heat removal by means of fluid (water), flowing through a heat exchanger thus producing power. The conclusion recorded upon observation are:

- The entire Thermoelectric Generator setup was successfully capable in generating power.
- The TEG module was capable enough as a power source to a 1W and a 5W LED bulb simultaneously when the hot side temperature was 175oC.
- The experimental setup of TEG modules can be successfully used for heat waste recovery from automobile exhaust. This may considerably contribute towards the call for energy saving and reduction of pollutants which is the emerging worlds need. In view of the growing threat towards global warming.

13. FUTURE SCOPE

Following are points being noted as to be carry out futureresearch and development in near future. These unit is still in the growing stage and has a potential of bright future. Intensive work is still being done upon the Waste heat recovery and thermoelectric unit combo. These are a bit expensive at this stage but once serves the purpose it may balance the investment.

- ✓ Output Voltage can be increased by proper and efficient use of respective heat sink.
- ✓ Make proper use of heat sink material heat between the fins can be avoided.
- ✓ Voltage can also be enhanced by adding many TEG’s in series.
- ✓ Use of more fin can increase the cooling rate alsoby reducing the temperature we can increase the temperature gradient.
- ✓ Long fin provides more gap results in avoiding heat accumulation.

14. References

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