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## Use of Heat Recuperator for Generation of Power through Thermoelectric Generator

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**ABSTRACT:** Generation of power through the waste heat recovered during a thermal process has always been a challenge for engineers. As the heat recovered may or may not be high enough to implement it for usage in a turbine as the movement for the blades of turbine should be high enough to alter the generator to produce the voltage. Thus there is a requirement that the waste heat should be high enough and implemented efficiently for the generation purpose.

Here in this analytical study a recuperator is used as a source for trapping the waste heat obtained. In a recuperator the heat exchange takes place between the flue gases and the air through metallic or ceramic walls. Duct or tubes carry the air for combustion to be pre – heated the other side contains the waste heat stream [1]. The hot flue gases will be implemented to heat the water stored in the copper tubes and this hot water will act as a hot junction for thermoelectric generator for the purpose of generation of voltage installed in series connection to each other. The power generated by the series combination of TEGs is up to 3KW. The voltage generated by the TEG is directly proportional to the temperature difference maintained between the two junctions.

The Thermoelectric Generator has proved to be an indispensable device for the generation of power through waste heat.

**KEYWORDS:** Flue gases, Recuperator, ceramic walls, heat stream.

### I. INTRODUCTION

Here, a silicon refinery is used as an example as the heat usage is at very high rate. The recuperator is used in to collect the waste flue gases for the purpose of reheating the fresh supply of air enter into the combustion chamber [1]. This flue gas can also be used to heat the water present in a thermosiphon. This task is carried out by using a convective type of recuperator which more efficient than other types of recuperators. The water which is filled in the copper tubes of the thermosiphon is heated at a temperature of near about 400 Celsius this water is used as a hot junction for the Thermoelectric generator which is connected in series in large number to produce a high voltage resulting in an output power of up to 3000 Watt.(Heat Recovery Systems by D.A. Reay, E & F.N. Span, London, 1979)

This form of heat usage for the generation of voltage is a new method which may require certain improvement. The advantage of using TEG here is that the flue gases provide heat energy which is ideal for the working of the thermoelectric module the heat energy is not enough to generate a constant amount of heat steam capable and powerful enough to run a turbine so that there is a continuous generation of voltage. Thus no moving parts can be implemented here for the purpose of generation of voltage. Moreover it also shows that TEG is the best option for generation of voltage through waste heat which is mostly unsuitable for implementation in running a turbine. (Fuel Economy in furnaces and Waste heat recovery-PCRA)

### II. RECUPERATOR

A recuperator is a waste heat recovery device which implements the waste flue gases to heat the atmospheric cold air. In a recuperator, heat exchange takes place between the flue gases and the air through metallic or ceramic walls. Duct or tubes carry the air for combustion to be pre-heated; the other side contains the waste heat stream. Recuperators are of

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many types based on their performance and the structural design. The convective and radiation type of recuperators are efficient one. Here in the research work the convective type recuperator is implemented with the usage of ceramic walls. A second common configuration for recuperators is called the tube type or convective recuperator [1]. As seen in the figure 1, the hot gases are carried through a number of parallel small diameter tubes, while the incoming air to be heated enters a shell surrounding the tubes and passes over the hot tubes one or more times in a direction normal to their axes. If the tubes are baffled to allow the gas to pass over them twice, the heat exchanger is termed a two-pass recuperator; if two baffles are used, a three-pass recuperator, etc [2]. Although baffling increases both the cost of the exchanger and the pressure drop in the combustion air path, it increases the effectiveness of heat exchange. Shell and tube type recuperators are generally more compact and have a higher effectiveness than radiation recuperators, because of the larger heat transfer area made possible through the use of multiple tubes and multiple passes of the gases. For maximum effectiveness of heat transfer, combinations of radiation and convective designs are used, with the high-temperature radiation recuperator being first followed by convection type. These are more expensive than simple metallic radiation recuperators, but are less bulky. [1]

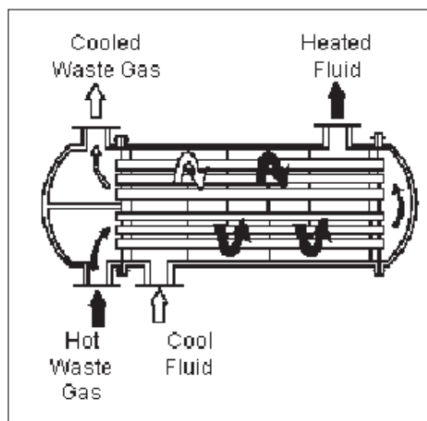


Figure -1 Convective Type Recuperator

### III. THERMOSIPHON

Thermosiphon is an effective heat transfer device that utilizes latent heat of the working fluid, flowing under the influence of gravity, to transport heat from the source to the sink. As the latent heat of vaporization is relatively high, the thermosiphons can transfer large quantity of heat with very small end to end temperature differential and thus low thermal resistance (Tabor et al., 1986).

$$Q_{oa} = \frac{\Delta T_{eff}}{Z_t} \tag{1}$$

Where,  $\Delta T_{eff}$  [K] is effective temperature difference between heat source and sink and defined by:

$$\Delta T_{eff} = T_{so} - T_{st} - \Delta T_h \tag{2}$$

Here,  $T_{so}$  is the heat source temperature and  $T_{st}$  is the heat sink temperature and  $\Delta T_h$  [K] is the mean hydrostatic temperature difference which is given as:

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$$\Delta T_h = (T_p - T_v) F / 2 \tag{3}$$

Where F is the filling ratio and defined by:

$$F = V_1 / A_{ts} * L_e \tag{4}$$

$V_1$  [m<sup>3</sup>] is the volume of the working fluid,  $A_{ts}$  [m<sup>2</sup>] is the internal cross section of the thermosiphon pipe and  $L_e$  [m] is the evaporator length.  $T_p$  [K] the saturation temperature at the bottom of the pool is given by:

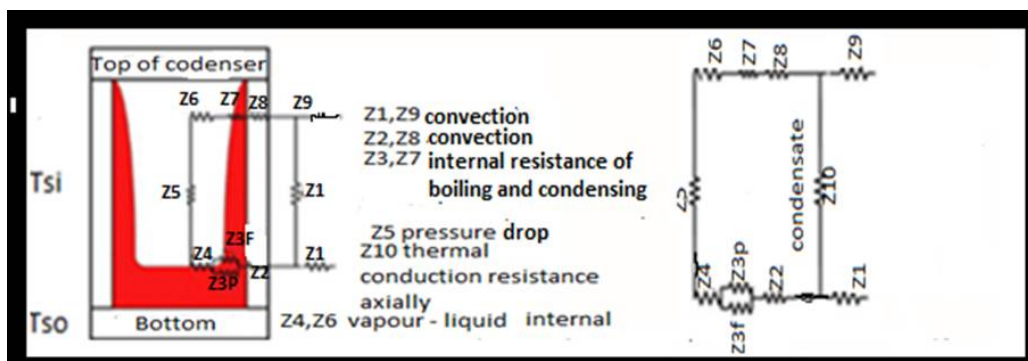
$$T_p = T_v + (L_e F * dT_s / dH) \tag{5}$$

In the above equation  $T_v$  [K] is the temperature of the vapour in the adiabatic and condenser section  $T_s$  [K] is the saturation temperature of the boiling liquid and  $H$  [m] is the hydrostatic height of the liquid in the evaporator. The total thermal resistance –  $Z_t$  [K/W] from heat source to the heat sink for thermosiphon is related to the actual overall heat transfer -  $x_{oa}Q$  [W] (Dunn, P. D et al., 1981).



**Fig. 2 Thermosiphon**

An ideal network of thermal resistance of  $Z_1$  to  $Z_{10}$  is shown in Figure 3.b. The individual thermal resistances as depicted in Figure 3 that make up the total thermal resistance from the heat source to the heat sink in the gravity assisted thermosiphon system is now discussed in detail (Dunn, P. D et al., 1981)



**Fig. 3 Thermal resistance and their location**

$Z_1$  and  $Z_9$  are thermal resistance between “heat source and the evaporator external surface” and “heat sink and condenser external surface” respectively. These can be expressed as:

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$$Z_1 = \frac{1}{h_{eo}S_{co}}$$

$$Z_9 = \frac{1}{h_{co}S_{co}}$$

(6)

$h_{eo}, h_{co}$  [W/m<sup>2</sup>.K] are evaporator and condenser outside heat transfer coefficient and  $S_{eo}, S_{co}$ [m<sup>2</sup>] are Evaporator and condenser external surface respectively (Faghri, A. et al., 1984).

$Z_2$  and  $Z_8$  are the thermal resistances present in the thickness of the thermosiphon tube wall in the “evaporative section” and “condenser section” respectively, which can be determined as:

$$Z_2 = \frac{\ln(D_o/D_i)}{2\pi L_e k_p}$$

$$Z_8 = \frac{\ln(D_o/D_i)}{2\pi L_c k_p}$$

(7)

Where  $D_o, D_i$  [m] are external and internal diameters of the thermosiphon tube  $L_e, L_c$  [m] are evaporator and condenser length and  $K_p$  [W/m.k] is the thermal conductivity of the thermosiphon pipe material.

$Z_3$  and  $Z_7$  are the internal resistances due to pool and film boiling of the working fluid which

$$Z_{3p} = \frac{1}{\Phi_3 g^{0.2} Q^{0.4} (\pi D_i L_e)^{0.6}}$$

(8)

Where,  $\Phi_3$  [K-1] is the figure of merit for the case of pool boiling

$$\Phi_3 = 0.325 \left( \frac{\rho_l^{0.5} k_l^{0.3} C_{pl}^{0.7}}{\rho_v^{0.25} h_{vl}^{0.4} \mu_l^{0.1}} \right) \left( \frac{P_v}{P_a} \right)^{0.23}$$

(9)

$Z_{3f}$  [K/W] is resistance from film boiling at the evaporator section:

$$Z_{3f} = \frac{C Q_o^{1/3}}{D_i^{4/3} g^{1/3} L_e \Phi_2^{4/3}}$$

(10)

Where C is constant of the cylinder tube

$$C = \left( \frac{1}{4} \right) \left( \frac{3}{\pi} \right)^{\frac{4}{3}} = 0.235$$

(11)

Where  $h_{v1}$ [W/KG] is the latent heat of evaporation of the working fluid,  $K_l$ [W/m.k] is the thermal conductivity of the working fluid in the liquid phase,  $\rho_l$  [kg/m<sup>3</sup>] is liquid density,  $\rho_v$ [kg/m<sup>3</sup>] is the vapour density,  $p_v$ [pa] is the vapour pressure and  $p_a$ [pa] is the atmospheric pressure.  $Z_4$  and  $Z_6$  are the thermal resistances that occur at the vapour liquid interface in the evaporator and condenser respectively (Faghri, A. et al., 1984).  $Z_5$  is the effective thermal resistances due to the pressure drop of the vapour as it follows from the evaporator to the condenser. The value of  $Z_5$  is quite small as compared to the value of  $Z_3$  and  $Z_7$ . AS the magnitude of  $Z_4, Z_5, Z_6$  and  $Z_{10}$  are negligible therefore these are generally neglected in the analysis therefore the overall thermal resistance is given by:

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$$Z_t = Z_1 + Z_2 + Z_3 + Z_7 + Z_8 + Z_9 \quad (12)$$

## IV. THERMOELECTRIC GENERATOR

Thermoelectric generator is a device that converts thermal energy directly into electrical energy. The TEG structure is “sandwich like”, with thermoelectric materials which are “sandwiched” by two heat exchanger plates at its ends respectively. One of the two exchangers is at high temperature, and hence, it is called the hot side of the TEG; while the other side is at lower temperature and is called the cold side of the TEG. There are electrical-insulated thermal-conductive layers between the metal heat exchangers and the TE material of TEG. The two ends of n- and p-type legs are electrically connected by metal. The structure of TEG is as shown in figure 4

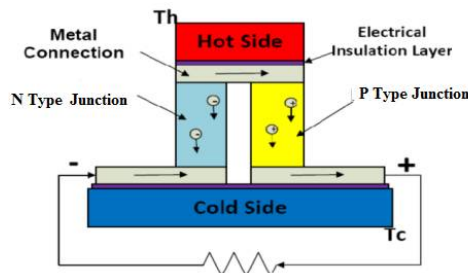


Figure - 4 Illustration of TEG

T –average temperature  $(T_2 + T_1)/2$  in the device (K),

$\sigma$  -Seebeck coefficient (V/K),

u- Current density ( $A/m^3$ ),

S-Compatibility factor (1/V)

It is clear that  $s$  depends on temperature of materials which is derived from other temperature dependent properties like  $\sigma$ ,  $\kappa$ , and  $\rho$ . It means that  $s$  cannot be changed with device geometry or the alteration of electrical or thermal currents.

Heat is supplied at hot side at temperature  $T_{hs}$  while the other end is maintained at a lower temperature  $T_{cs}$  by a heat sink. As a result of the temperature difference, current  $I$  flow through an external load resistance  $R_{ex}$ . The power output depends on the temperature difference, the properties of the semiconductor materials and the external load resistance.

For a TEG composed of  $n$  thermoelectric generating elements as shown by block diagram in Figure 3, the following parameters can be calculated and rate of heat supply is given by these equations:

$$Q_{hs} = \alpha I T_{hs} - 0.5 I^2 R_i + k_{teg} (T_{hs} - T_{cs})$$

Rate of heat removal

$$Q_{cs} = \alpha I T_{cs} - 0.5 I^2 R_i + k_{teg} (T_{hs} - T_{cs})$$

Output voltage

$$V = \alpha (T_{hs} - T_{cs}) - I R_i$$

Useful output power

$$P = \alpha I (T_{hs} - T_{cs}) - I^2 R_i$$

Each thermoelectric element is assumed to be insulated, both electrically and thermally, from its surroundings, except at the junction to hot/cold reservoir contacts. The internal irreversibility for the TEG is produced by Joule electrical resistive loss and heat conduction loss through the semiconductors between the hot and cold junctions. The Joule losses generate internal heat equal to  $I^2 R_i$  where  $I$  [A] is electric current generated by thermoelectric generator,  $R_i$  [ $\Omega$ ] is the total internal resistance of the thermoelectric generator. Conduction heat loss is  $k_{teg} (T_{hs} - T_{cs})$  where,  $k_{teg}$  [W/m.K] is thermal conductivity of thermoelectric generator. The external irreversibility is caused by finite rate heat transfers at the source and the sink.[8,10] For a TEG composed of  $n$  thermoelectric generating elements as shown by block diagram in Figure 4, the following parameters can be calculated (Tabor et al., 1986).

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## V. EXPERIMENTAL SET UP

A connection is made between the flue gases coming from the chimney of the refinery to the recuperator and this recuperator passes the hot gas towards the thermosiphon which holds the sea water for the boiling. The boiled water gets transmitted to the thermoelectric generator where it serves as a hot junction for the TEG. Thus, a constant supply of hot water to the hot junction of the thermoelectric generator ensures a constant temperature difference in the thermoelectric module which results in the constant voltage production.[4]

The figure below shows the scheme of the experiment.

A high voltage is produced from the following scheme provided if the TEGs are used in a large number connected in series to each other.

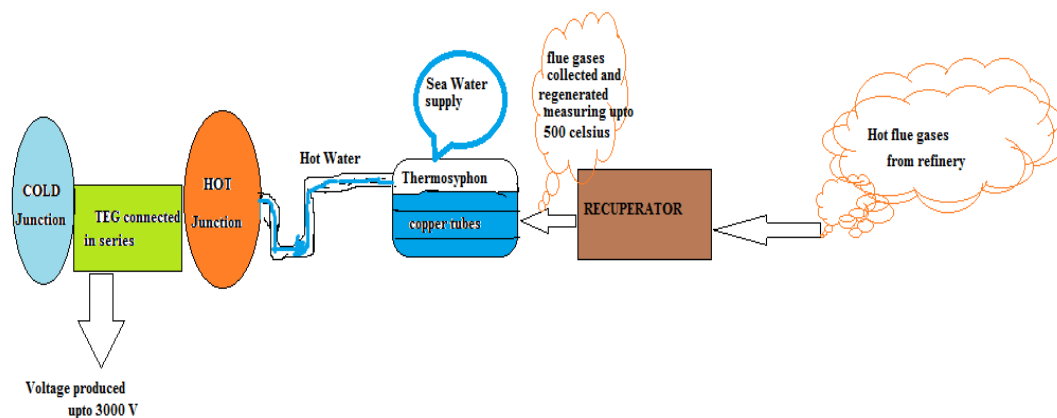


Figure 6 - Schematic Block Diagram

## VI. MATLAB CODING OF THE EXPERIMENTAL SET UP

### Thermosiphon

```
%----Mathematical Modelling of the Thermosiphon-----
% Q_oa = overall Heat transfer
% Del_Teff = Effective Temp difference between Heat Source and Sink
% T_so = Heat Source Temperature
% T_si = Heat Sink Temperature
% Del_Th = Mean Hydrostatic Temperature difference
% T_p = saturation Temp at bottom of the pool
% T_v = Temperature of vapour adiabatic and Condenser
% F = Filling Ratio
% V_l = Volume of working Fluid
% A_ts = Internal Cross-section of Thermosiphon Pipe
% L_e = Length of Evaporator
% L_c = Length of Condenser
% L_i = Length of Insulation section
% T_s = Saturation temperature of Boiling Fluid
% del_T_s_H = rate of temp change of boiling liquide with heat
% H = Hydrostatic Height of the Liquid of the Evaporator
% Z_t = Total Thermal resistance from Heat Source to Heat Sink
% Z_1, Z_9 = Thermal resistance at Convection zone
```



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```

% Z2, Z8 = Thermal resistance at Convection zone
% Z3, Z7 = Internal Resistance of Boiling and Condensing
% Z5 = Pressure Drop
% Z10 = Thermal Conduction resistance
% Z4, Z6 = Vapour- liquid internal thermal resistance
% heo= EvaporatorOutside Heat transfer Coefficient
% hco= Condenser Outside Heat transfer Coefficient
% Seo= Evaporator external surface (m2)
% Sco= Condenser external surface (m2)
% Do= External Diameter of Thermosiphon tube
% Di= Internal Diameter of Thermosiphon tube
% kp= Thermal Conductivity of Thermosiphon Pipe Material
% phi3 = Figure of Merit for case of pool boiling
% Z3f = Resistance of film boiling at evaporator section
% Z3p = Resistance of pool boiling at evaporator section
% C = Constant of Cylinder tube
% hv= latent heat of evaporation of working fluid
% kl= thermal Conductivity of the working fluid in liquid phase
% rhol= liquid density
% rhov= vapour density
% Pv= vapour Pressure
% Pa= Atmospheric Pressure
% Cpl = liquid specific heat capacity at constant pressure
% hvl = latent heat of evaporation
% mul = liquid dynamic viscosity
% rhol = liquid density
%-----
L = Le + Lc + Li;
Z1 = 1/(heo*Seo);
%fprintf("\n Z1 = %d',Z1);
Z9 = 1/(hco * Sco);
fprintf("\n Z9 = %d',Z9);
Z2 = ((log(Do/Di))/(2*pi*Le*kp));
fprintf("\n Z2 = %d',Z2);
Z8 = ((log(Do/Di))/(2*pi*Lc*kp));
fprintf("\n Z8 = %d',Z8);
phi3 = ((0.325)* (((rhol)^(0.5))* ((kl)^(0.3))* ((Cpl)^0.7))/(((rhov)^0.25)* (hvl^0.4)*(mul^0.1))*((Pv *
Pa)^0.23));
fprintf("\n phi3 = %d', phi3);
C = ((1/4) * ((3/pi)^(4/3))); %Constant of cylinder tube
fprintf("\n C = %d',C);
phi2 = ((Le * kl^3 * rhol^2)/(mul)^(1/4)); % K-1: figure of merit of boiling case
fprintf("\n phi2 = %d', phi2);
Z3p = (1/(phi3 * (g^(0.2)) * (Q^(0.4)) * ((pi*Di*Le)^0.6)))
Z3f = ((C*(Q^(1/3)))/((Di^(4/3)) * (g^(1/3)) * (Le) * ((phi3)^(4/3))));
if Z3p > Z3f
    Z3 = Z3p;
fprintf("\n Z3 = %d',Z3);
else

```

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```

Z3 = (Z_3p*F) + (Z_3f * (1-F));
fprintf("\n Z3 = %d',Z3);
end
Z7 = ((C*(Qo^(1/3)))/ ((D_i^(4/3))*(g^(1/2))*L_c * (phi_2 ^ (4/3))));
fprintf("\n Z7 = %d',Z7);
Z_t = Z1 + Z2 + Z3 + Z7 + Z8 + Z9; % Total Thermal resistance from Heat Source to Heat Sink
fprintf("\n Total ThermResistance = %d\n', Z_t);
F = (V_l/ (A_ts * L_e));
fprintf("\n F = %d',F);
del_T_s_H = (((T_s * g)/L)* ((rho_l/rho_v)-1));
fprintf("\n dTs/dH = %d',del_T_s_H);
T_v = T_si + ((Z7 + Z8 + Z9)/(Z_t))* (T_so - T_si);
fprintf("\n T_v = %d',T_v);
T_p = T_v + (L_e*F* del_T_s_H);
fprintf("\n T_p = %d',T_p);
del_Th = ((T_p - T_v)*F)/2;
fprintf("\ndel_Th = %d',del_Th);
del_Teff = T_so - T_si - del_Th;
fprintf("\ndel_Teff = %d',del_Teff);
Q_oa_dot = (del_Teff / Z_t); % Heat pr unit mass per sec
fprintf("\n Q_oa_dot (per unit mass) = %d',Q_oa_dot);
dt = 1;
Q_oa = Q_oa_dot * dm * dt;
fprintf("\n Q_oa(Actual) = %d',Q_oa);

```

### Thermoelectric Generator

```

%----Mathematical Modelling of the thermoelectric generator-----
% Q_hs    = Rate of Heat supply
% Q_cs    = Rate of Heat Removal
% V_out   = Output voltage
% P_out   = Output power
% alpha   = Seebeck coefficient of the thermocouple Elements
% I_out   = Output current
% R_i     = Internal Resistance
% k_teg   = Thermal conductivity of TEG
% T_hs    = temperature at supply point
% T_cs    = Temperature at sink
% R_ex    = External Resistance--- Load resistance
% V_load  = voltage across Voltage
% N       = No of cells
%-----
R_ext = 2.1e-1;
T_hs = T_so;
T_cs = T_si;

V_gen = N * (alpha * (T_hs - T_cs));
fprintf("\n Gen. voltage = %d \n',V_gen);
%R_i =V_gen/ I_sc;%Total internal electrical resistance of the TEG

```



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```
R_i = N*(rho_TEG * (L_TEG/A_TEG));  
fprintf("\n R_i = %d \n",R_i);  
  
I_sc = V_gen/R_i ;  
fprintf("\n I_sc = %d \n",I_sc);  
  
I = V_gen/(R_ext + R_i);  
fprintf("\n Current = %d \n",I);  
  
Q_hs = ((alpha * I *T_hs) - (0.5 * I^2 * R_i) + (k_teg * (T_hs - T_cs)));  
fprintf("\n Rate of Heat supply = %d \n",Q_hs);  
  
Q_cs = ((alpha * I *T_cs) - (0.5 * I^2 * R_i) + (k_teg * (T_hs - T_cs)));  
fprintf("\n Rate of Heat Removal = %d \n",Q_cs);  
  
V_out = I * R_ext;  
fprintf("\n Load voltage = %d \n",V_out);  
  
P_out = (N*alpha * I*(T_hs - T_cs)) - ((I^2)*R_i) ;  
fprintf("\n Output power = %d \n",P_out);
```

### VII. PROGRAM OUTPUT

```
>>>init_grid_param  
>>>ThermosiphonAnalysis  
Z1 = 2.719689e-03  
Z2 = 1.119355e-04  
Z8 = 3.731184e-04  
phi_3 = 6.258011e+02  
C = 2.350906e-01  
phi_2 = 9.442990e+01  
Z3 = 1.643065e-03  
Z7 = 7.774636e-03  
Total Therm Resistance = 1.355393e-02  
F = 1  
dTs/dH = 1.985612e+02  
Tv = 3.050717e+02  
Tp = 3.646401e+02  
del_Th = 2.978418e+01  
del_Teff = 1.021582e+01  
Q_oa_dot (per unit mass) = 7.537159e+02  
Q_oa(Actual) = 1.789322e+02>>> TEG Module  
Gen. Voltage = 1.080000e+02  
R_i = 6.210000e-02  
Isc = 1.739130e+03  
Current = 3.969129e+02  
Rate of Heat supply = 1.199522e+07  
Rate of Heat Removal = 1.199521e+07  
Load voltage = 8.335171e+01  
Output power = 3.308337e+04
```

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## VIII. GRAPHICAL PLOT

Figure - 1

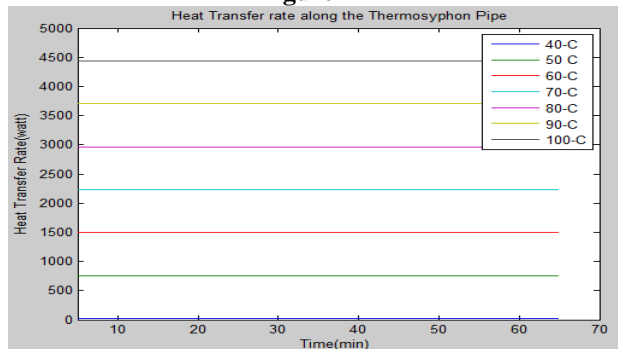


Figure -2

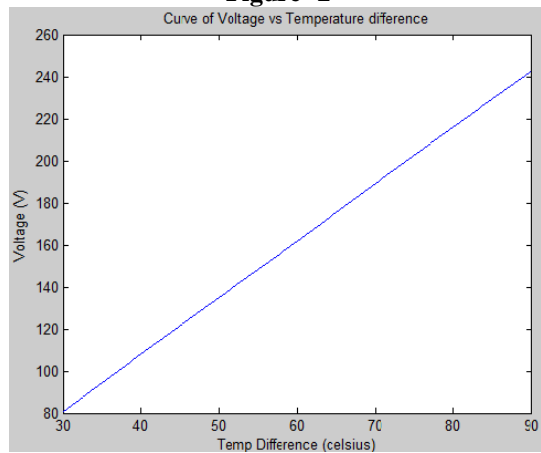
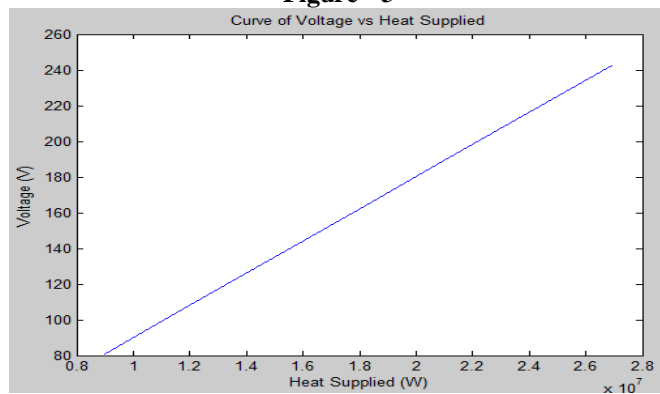


Figure - 3



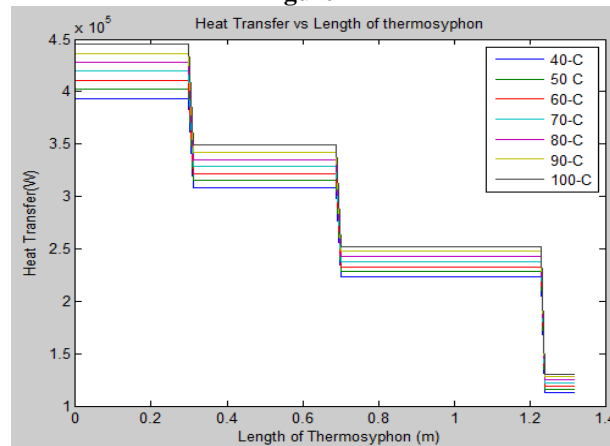
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Figure - 4



## IX. CONCLUSIONS

By doing this work it can be concluded that the scope of generation of electrical energy from the Thermoelectric generator is vast, the hot junction for a TEG can be made through any source of heat energy available which can be even the waste heat generated by the automobiles or the manufacturing industries.

The voltage produced here by the process of Seebeck effect may range from milli-volt to volts this depends upon the thermoelectric module used to create the generator, the number of TEGs used when connected in series or parallel, the temperature difference created by the two junctions and the ability of the material withstand the great amount of heat produced. In the journal it has been showed that the waste heat which was obtained in during the process of refining a mineral in the form of flue gases can be implemented in with the help of a recuperator which functions to heat the air entering via the flue gases. The hot flue gases heat the water in the thermosiphon to which they are made to pass the thermosiphon which provides the hot water to the hot junction of the thermoelectric generator thus maintaining a desirable temperature difference essential for the generation of voltage through the TEG. The amount of voltage produced is up to 3200W which is obtained by the series combination of TEGs in large number.

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