Optimization of Efficiency of Kota Thermal Power Plant by Utilization of Waste Heat during Phase Change

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Abstract: *Neno materials play an important role in improving heat transfer rate and converting the available energy into optimum output. Condenser in a thermal power plant is the major cause of heat waste during phase change. During this phase change in condenser the efficiency of whole power plant can be optimized by utilizing waste heat available and at the same time the environmental pollution due to thermal energy can be reduced with prime objective to attain clean and efficient power generation. In the present paper, we convert some of the condenser wasted energy into electricity using thermoelectric material. By selecting suitable thermoelectric material and after required calculations we can design thermoelectric generator to be used as the condenser of 210 MW unit of kota thermal power plant. It is seen that about 3.3% efficiency of the said power plant during phase change is expected to be optimized by using the designed thermoelectric generator.*

Keywords: Thermoelectric Generator, Waste Heat, Efficiency, Improvement, Nano Material, Seeback Effect

1. Introduction K.T.P.P

Kota thermal power plant was established in 1983. It is having 7 units till date (total capacity-1240MW). The description of the seven units is as following.

Stage ▲	Unit Number ⬍	Installed Capacity (MW) ⬍	Date of Commissioning ⬍	Status ⬍
Stage I	1	110	January 1983	Running
Stage I	2	110	July, 1983	Running
Stage II	3	210	September 1988	Running
Stage II	4	210	May, 1989	Running
Stage III	5	210	March 1994	Running
Stage IV	6	195	July, 2003	Running
Stage V	7	195	May 2009	Running

2. Thermal Power Plant

Thermal power plants use water as working fluid. Nuclear and coal based power plants fall under this category. The way energy from fuel gets transformed into electricity forms the working of a power plant. In a thermal power plant a steam turbine is rotated with help of high pressure and high temperature steam and this rotation is transferred to a generator to produce electricity. Thermal power plant basically works on rankine cycle.

There are four processes in the Rankine cycle:
1. Water enters the pump as saturated liquid and compressed isentropially to the operating pressure of the boiler.
2. Saturation water enter the boiler and leaves it as superheated vapour.
3. Superheated vapour expands isentropically in turbine and produces work.
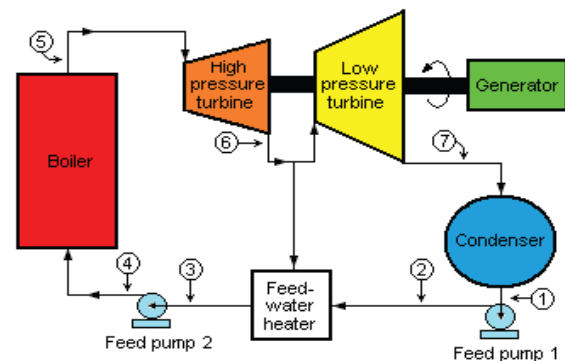4. High quality steam is condensed in the condenser.

Figure 1: Thermal power plant cycle

Working:-
Water is converted to (371°C) steam in the boiler and (371°C) steam is separated from water in the boiler Drum. The saturated steam from the boiler drum is taken to the Low Temperature Superheater, Platen Superheater and Final Superheater respectively for superheating. The superheated steam (535°C) from the final superheater is taken to the High Pressure Steam Turbine (HPT). In the HPT the steam pressure is utilized to rotate the turbine and the resultant is rotational energy. From the HPT the out coming steam is taken to the Reheater in the boiler to increase its temperature as the steam becomes wet at the HPT outlet. After reheating this steam is taken to the Intermediate Pressure Turbine (IPT) and then to the Low Pressure Turbine (LPT). The outlet of the LPT is sent to the condenser for condensing back to water by a cooling water system. This condensed water is collected in the Hotwell and is again sent to the boiler in a closed cycle. The rotational energy imparted to the turbine by high pressure steam is converted to electrical energy in the Generator.

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The steam is condensed for re-use. During this process the latent heat of condensation is lost to the cooling water. This is the major loss and is almost 40 % of the energy input.

In this paper, we decide to design a thermoelectric (TE) generator to produce electricity from some amount of the wasted heat in the condenser.

TE generator is designed for a 210 MW unit of thermal power plant. the efficiency of the selected power plant increases from 37% to 40.32%.

3. Rankine Cycle

Rankine cycle is a cycle that converts heat into work. the heat is supplied extremely to a closed loop. Which usually use water. This cycle generate about 90% of all electric power used throughout the world. The Rankine cycle is a steam cycle for a steam plant operating under the best theoretical conditions for most efficient operation.

Working

Rankine cycle consists of a boiler, turbine, condenser and a pump. Fuel, burned in the boiler, heats the water to generate superheated steam. This steam is used to run the turbine which powers the generator. Electrical energy is generated when the generator windings rotate in a strong magnetic field. After the steam leaves the turbine, it is cooled to its liquid state in the condenser by transferring heat to the cooling water system. The liquid is pressurized by the pump prior to going back to the boiler. All four components associated with the ideal Rankine cycle are steady-flow devices, and thus all four processes that make up the Rankine cycle can be analyzed as steady-flow process. The kinetic and potential energy changes of water are small relative to the heat and work terms, are thus neglected.

1-2 isentropic pump: W_{pump} is the consumption power of the water pump in process
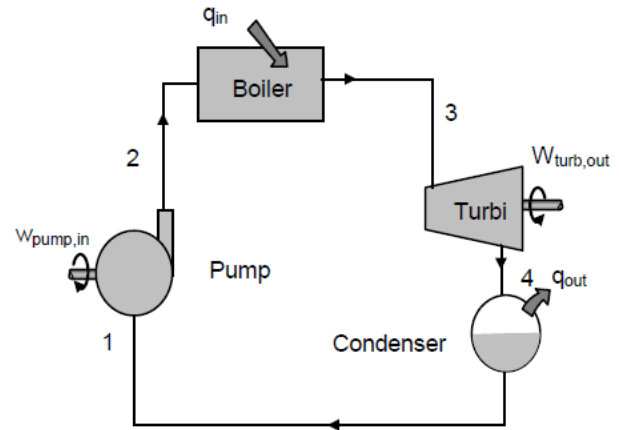
2-3 constant pressure heat addition: Q_{in} is the heat energy given to the water in process.

3-4 isentropic turbine: $W_{turbine}$ is the turbine produced power to electrical generator in process

4-1 constant pressure heat rejection: Q_{out} is the heat rejection to condensation in process.
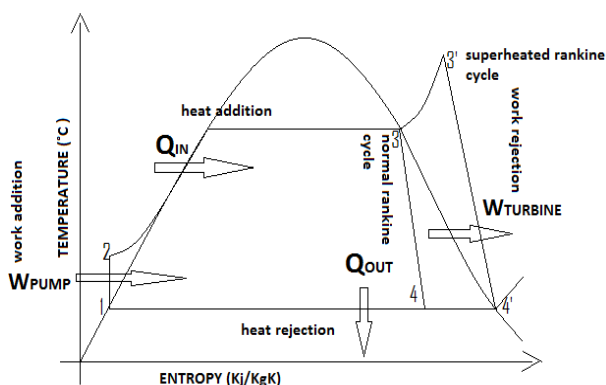
Figure 2: Normal and Superheated Rankine cycle

Figure 3: Power Plant Cycle

The efficiency of rankine cycle which is named thermodynamic efficiency can be declared as:

$$\eta_T = \frac{W_{turbine} - W_{pump}}{Q_{in}} \approx \frac{W_{turbine}}{Q_{in}} \quad (1)$$

4. Thermal Power Plant Condenser

The condensers and cooling systems involved in condensing the exhaust steam from a steam turbine and transferring the waste heat away from the power station.
Types of Steam Condenser
A. Jet Steam Condense
B. Surface Steam Condense

Surface Steam Condense
1. Shell and tube condenser
2. Evaporative condenser

Shell and Tube Condenser
The thermal power plant condenser shown below is a water-cooled shell and tube heat exchanger installed on the exhaust steam from a steam turbine in thermal power stations. These condensers are heat exchanger which convert steam from its gaseous to its liquid state at a pressure below atmospheric pressure. Where cooling water is in short supply, an air-cooled condenser is often used. An air-cooled condenser is however, significantly more expensive and cannot achieve as low a steam turbine exhaust pressure (and temperature) as a water-cooled surface condenser.

Working:-
Shell and tube heat exchangers consist of a series of tubes. One set of these tubes contains the fluid that must be either heated or cooled. The second fluid runs over the tubes that are being heated or cooled so that it can either provide the heat or absorb the heat required. A set of tubes is called the tube bundle and can be made up of several types of tubes: plain, longitudinally finned etc. Shell and Tube heat exchangers are typically used for high pressure applications (with pressures greater than 30 bar and temperatures greater than 260°C).

Practically 40% from the input power is lost during the condensation process where the energy from the steam will be rejected towards atmosphere. This can be the major loss in the thermal electric power plant.
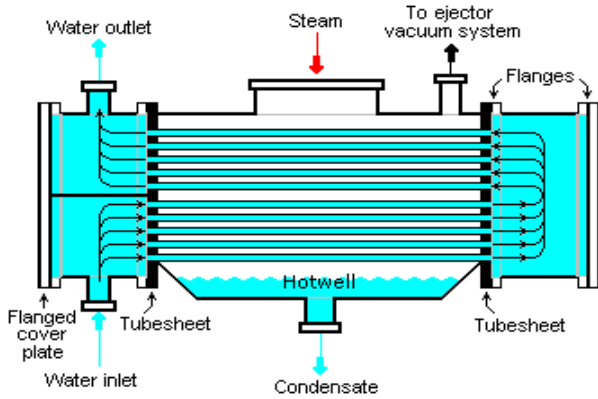
Figure 4: Thermal power plant condenser

5. Thermoelectric Generator

Thermoelectric power generator is a device that converts the heat energy into electrical energy based on the principles of Seebeck effect.

Seebeck Effect
When the junctions of two different metals are maintained at different temperature, the emf is produced in the circuit. This is known as Seebeck effect.

Principal
Thermoelectric power generator based on the principle of Seebeck effect that when the junctions of two different metals are maintained at different temperature, the emf is produced in the circuit.

Working:-
A thermoelectric generator consists of two thermoelectric semiconductors (n-type and p-type) subjected to a temperature difference, $T_{HOT} - T_{COLD}$, and electrically connected in series through conducting plates on the top and bottom. In the n-type semiconductor, most charge carriers are negatively charged electrons, whereas in the other one most of the carriers are positively charged holes. In a temperature gradient, electrons and holes tend to accumulate on the cold side. An electric field E develops between the cold side and the hot side of each material, which gives a voltage when integrated over the length of each. The voltages of the n- and p-type semiconductors add up and drive an electrical current through an electrical load, here an electrical resistor. The product of the voltage and the current is the electrical power output of the generator.

Thermoelectric Material
The good thermoelectric materials should possess.
- Large Seebeck coefficients
- High electrical conductivity
- Low thermal conductivity
Calculation of TE material:-

$$\text{Figure-of-merit } ZT = \alpha^2 \sigma T / \kappa \qquad (2)$$

Where
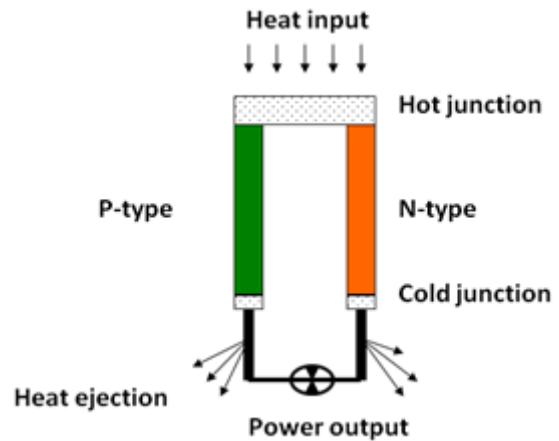seebeck coefficient - α(V/K)
electrical conductivity - σ(S/m)
thermal conductivity - κ(W.m^{-1}.K^{-1})

$$\text{Electrical resistivity } \rho = \frac{1}{\sigma} \rho \text{ (}\Omega\text{m)} \qquad (3)$$

$$\text{Thermal conductivity } \kappa = \kappa_{electron} - \kappa_{phonon} \qquad (4)$$

$$\text{Wiedmann} - \text{Franz law } \kappa_{electron} = L.\sigma.T \qquad (5)$$

Where, L is the Lorenz number ($2.445 \times 10^{-8} W.S^{-1}.K^{-2}$)

Figure 5: Thermoelectric generator structure.

The best thermoelectric material would behave as a ''phonon glass, electron-crystal'' (PGEC) that is, it would have the electrical properties of a crystalline material and the thermal properties of an amorphous or glass-like material. The materials with low thermal conductivity as in a glass, and a high electrical conductivity as in crystals are desired, while because of the physical characteristics of usual TE materials, these two parameters change in a similar way. So, the improvement of the TE materials ZT and also efficiency is so hard. But current researches on nano composite materials show that their ZT (and also their efficiency) is able to improve.

According to (2) and also the units of α and κ, ZT changes with temperature variation. In fact, the amount of the ZT, in the desired temperature, is one of the most important parameters to choose a TE material.

Thermoelectric Generator Equations

$$\text{Temperature difference } \Delta T = T_{Hot} - T_{Cold} \qquad (6)$$

$$\text{The open circuit output voltage Voc} = \alpha. \Delta T \qquad (7)$$

$$\text{Output current } I = V_{OC} / (R + R_L) \qquad (8)$$

TE generator internal resistance
$$R = \rho l / A \qquad (9)$$
Where
l is the length
A is the cross sectional area of the TE pellets
R_L is the load resistance which is set 1.323393R, for optimum efficiency.

$$\text{Output power } P = I^2. R_L \qquad (10)$$

Input heat to the TE generator
$$Q_H = \alpha. I. T_H - 0.5R. I^2 + K. \Delta T \qquad (11)$$

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Where K is:

$$K= \kappa.A \, /l \qquad (12)$$

TE pellet wasted heat

$$Q_C = Q_H - P \qquad (13)$$

TE pellet efficiency

$$\eta = P/Q_H \qquad (14)$$

6. Thermoelectric Steam Condenser Design

Here we select a 210MW unit thermal power plant. The efficiency of thermal power plant is typically around 37% so the input fossil fuel energy (P_f) is:

$$P_f = 210 \, / \, 0.37 \approx 567.56 \text{ MW} \qquad (15)$$

About 40 % of the input energy is wasted during the condensation process. So the input energy of the condenser (P_C) is calculated as:

$$P_c = 567.56 \times 0.4 = 227.02 \text{ MW} \qquad (16)$$

BISMUTH TELLURIDE (Bi_2Te_3) TE PELLET
Nanowires Size 6×6×1 mm
Seebeck Coefficient 287 μV/K at 327 Kelvin
High Electrical Conductivity 1.1×10^5 S/m
Very Low Lattice Thermal Conductivity 1.20 $W.m^{-1}.K^{-1}$
Melting Point 858 Kelvin
Working Temperature - Between 300 to 400 Kelvin.
The material figure-of-merit, from (2), is:

$$ZT = [(287 \times 10^{-6})^2 . (1.1 \times 10^5). (327)]/(1.20) = 2.47 \quad (17)$$

Here, the temperature of the wet steam entered the condenser which is also the temperature of the hot side of the TE pellet, is supposed: T_H =400K. The temperature of the cold side of the TE pellet is: T_C = 300 K, so from (6) and (7):

$$\Delta T=400 \text{ -}300 = 100 \text{ K} \qquad (18)$$
$$V_{oc}=(287 \times 10^{-6}).100 = 28.7 \text{ mV} \qquad (19)$$

From (3), the electrical resistivity is:

$$\rho =1/\sigma=1/(1.1 \times 10^5) = 9.09 \times 10^{-6} \, \Omega.m \qquad (20)$$

From (9), the internal resistance is:

$$R=(9.09 \times 10^{-6}). (1 \times 10^{-3})/(6 \times 6 \times 10^{-6}) = 0.252 \text{ m} \quad (21)$$

So R_L is:

$$R_L =1.323393R = 0.334 \text{ m}\Omega \qquad (22)$$

As a result, from (8) and (10):

$$I= (28.7) \, / \, (0.252 + 0.334) =48.98 \text{ A} \qquad (23)$$
$$P=(48.98)^2.(0.334 \times 10^{-3}) = 801.28 \text{ mW} \qquad (24)$$

From (12) and (11), K and the pellet input heat power is:

$$K= [(1.20). (6 \times 6 \times 10^{-6})] \, / \, (1 \times 10^{-3}) = 0.0432 \qquad (25)$$

$$Q_H = [(287 \times 10^{-6}). (48.98). (400)] - [0.5 (0.252 \times 10^3).$$
$$(48.98)^2] + [(0.0432). (100)] = 9.640 \text{ W} \qquad (26)$$

The wasted heat is calculated from (13):

$$Q_C = 9.640 - 0.801 = 8.839 \text{ W} \qquad (27)$$

So the efficiency from (14) is:

$$\eta = (0.801/ \, 9.640) \times 100 = 8.31\% \qquad (28)$$

As P_c = 227.02 MW, so the output power of the TE Generator (P_{Cout}) is:

$$P_{Cout} = 227.02 \times (8.31 \, / \, 100) =18.86 \text{ MW} \qquad (29)$$

The number of pellets needed to produce the power is:

$$N_R = (18.86 \times 10^6) \, / \, (0.801) = 23545568.04 \approx$$
$$= 23545568 \qquad (30)$$

The area needed for 23545568 pellets:

$$S_R = 23545568 \times (6 \times 6 \times 10^{-6}) = 847.64 \, m^2 \qquad (31)$$

The total output power of the power plant is now:

$$P_{O \, total} = 210+18.86 = 228.86 \text{ MW} \qquad (32)$$

The total efficiency of the thermal power plant is Calculated as:

$$\eta_{total} =100 \times 228.86 \, / \, 567.56 = 40.32 \text{ \%} \qquad (33)$$

7. Conclusion

The major losses of thermal power plants are in condenser in which the steam changes into the water after rotating the turbine. In the condensation processes 40% of the input fuel energy is wasted.

In the paper, Bi_2Te_3 nanowires material is used as TE generator in the thermal power plant condenser to convert waste heat to electricity. The figure of merit and also the operational temperature of the TE materials are important factors to choose a TE material for a particular application. The maximum figure of merit of the selected TE material is in temperature of about 327 K which is around the temperature the of the steam entered the condenser.

It was calculated that by using the designed TE generator, about 18.36 MW of the wasted heat in the 210 MW thermal power plant could be converted to electricity. The designing increased the electricity generation efficiency for about 3.3%.

8. Challenges In Future

The efficiency of the selected TE material was calculated about 8.31%. Using different type of materials, different size nanowire, reduction of number of pellets. New and more efficient TE materials for power generation in the

condensation cycle of thermal power plant is offered as a future work.

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