Efficiency improvement in thermal power plants using waste heat recovery of flue gas – simulation study.

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Abstract. In this paper an Organic Rankine cycle is used as waste heat recovery cycle for a 250 x 2 MW thermal power plant. The exhaust flue gas (80 to 130°C) in the thermal power plant is often released into the atmosphere as waste heat. This waste heat can be utilized as a form of heat source for the Organic Rankine Cycle. The treated flue gas form the Flue Gas Desulphurization plant will be fed to the heat exchanger where the heat transfer between the flue gas and the working fluid (e.g.: Ammonia, R245A) will take place. The working fluid will be fed to the (low pressure) turbine where the work done can obtained. After the expansion of the working fluid in the turbine, the working fluid is cooled in the condenser using water. Then this fluid is again sent to the heat exchanger using pump. The flue gas from the heat exchanger after the heat transfer will be then supplied to the stack. The cooling of the condenser water can be done using a cooling tower. As the load varies for the thermal power plant the temperature of the flue gas also changes and hence the turbine shaft output also changes this may result in tripping of the generator. In order to avoid this, a turbine governing system is designed with a step-up gear box and a torque converter. This governing system will keep the generating shaft in motion at constant speed even during low loads and high loads. This cycle will help the thermal power plants to obtain extra power output and will increase the efficiency of the plants.

1. Introduction
The thermal power plants or pulverized coal fired plants are one of the major sources of the power in India and all over the world. This plants function based on the Rankine cycle. The efficiency of this plants is up to 38-40%. The flue gas from the boiler of the plant carries some of the heat from the boiler along with ash and this heat is let out in the atmosphere after the treatment process of the flue gas. A waste heat recovery system can be used to obtain work using the waste flue gas heat. The addition of this cycle will result in increase in efficiency of the power plant and power output from the recovery cycle.

The flue gas is drawn from the boiler, passing through electrostatic precipitator with the help of induced draft fans and is fed to the flue gas desulphurization plant where the SOx concentration is removed from the flue gas. The flue gas before entering the scrubber house of the plant is passed through the Gas to gas heat exchanger, where the heat of the flue gas is extracted and is given to the low temperature flue gas from the scrubber house with low SOx concentration. This flue gas from the
gas to gas heat exchanger outlet has temperature of about 80-134°C. This gas is then given to an evaporator mainly a shell and tube heat exchanger. The flue gas is given on the shell side and after the heat exchange the gas is given out from the stack of the power plant.

On the tube side of the evaporator organic fluid such as 1,1,1,3,3-Pentafluoropropane (R-245FA) with low boiling point and at high pressure will be present which will be evaporated due to the high temperature obtained from the heat transfer from the flue gas. Then the organic fluid will be then fed to the turbine with help of nozzles and valves. When the fluid will enter the turbine, it will exert the force on the turbine blades and the turbine will start rotating and work done will be obtained from the turbine shaft. After the expansion of the organic fluid in the turbine it will be given to the condenser mainly shell and tube type. The fluid will be cooled into liquid state using water from the cooling tower. The cooled fluid will be then given to the pump which will increase the pressure and will keep the fluid in the liquid state. Then again, this pressurized fluid will be given to the evaporator. This cycle of the organic fluid will be completely closed cycle hence there will be no loss of organic fluid in the cycle.

As the temperature of the flue gas will be variable as per the load the work done by the turbine will also vary. Hence to protect the generator from getting overheated due to additional work done an additional turbine governing system will also be introduced. This turbine governing system consist of a step-up gear box and fluid coupling.

2. The organic rankine cycle for the waste heat recovery

The Organic Rankine Cycle consist of an evaporator, turbine, condenser, pump, hydraulic gear box and generator. The organic Rankine cycle has the same principle as that of the Rankine cycle, except for the working fluid which is steam in the Rankine cycle and organic fluid in ORC such as R245FA. The working fluid is pumped to an evaporator where it is superheated, and it undergoes expansion process in the turbine and then through a condenser. The organic fluid will be cooled in the condenser with help of a cooling tower. The expansion device will be linked to the generator using a hydraulic gear box. This cycle will be a closed cycle.

The waste heat recovery cycle is also called as vapour power cycle. The process for the ORC cycle is as follows:

1. The first process: In the Evaporator i.e. shell and tube heat exchanger the organic fluid undergoes a reversible constant pressure heating process of the organic fluid from liquid to vapour (Superheated).
2. The second process: In the Turbine the organic fluid undergoes a reversible adiabatic expansion process. The turbine used for the cycle is an isentropic turbine with discharge pressure of 2 bar.
3. The third process: In the Condenser the organic fluid undergoes reversible constant pressure heat rejection process till the vapour of the organic fluid condenses to saturated liquid.
4. The fourth process: The Pump is used for the reversible adiabatic compression of the organic fluid to the initial pressure.

Accordingly, the steady flow energy equations for all the process are as follows:

1. The SFEE for the evaporator is:
   \[ Q_1 + h_4 = h_1 \]
   \[ Q_1 = h_1 - h_4 \]  
   (1)

2. The SFEE for the Turbine is:
   \[ h_1 = W_T + h_2 \]
   \[ h_1 - h_2 = W_T \]  
   (2)
3. The SFEE for the Condenser is:

\[ h_2 = Q_2 + h_3 \]

\[ h_2 - h_3 = Q_2 \]  

(3)

4. The SFEE for the Pump is:

\[ W_P + h_3 = h_4 \]

\[ W_P = h_4 - h_3 \]  

(4)

5. The efficiency of the cycle is given by:

\[ \eta = \frac{W_{net}}{Q_1} \]

\[ = \frac{(W_T + W_P)}{Q_1} \]  

(5)

The SFEE can be calculated from the plant parameters and the thermodynamic properties of the organic fluid. The efficiency of the cycle can be further calculated by substituting the values based on the thermophysical properties of the refrigerants.

3. ORC and software cycle set-up

The software used for the simulation of the ORC waste heat recovery is ASPEN V9. The data of the organic fluid, water, etc. were used to simulate the cycle. The flue gas properties were added to the system which were obtained from the power plant over certain duration at 250MW load which are given below,

| Table 1. Parameters for the cycle. |
|-----------------------------------|
| Parameters     | Temperature (°C) | Pressure (mmWC) |
| Gas to gas heater inlet. | 132            | 123            |
| Gas to gas heater outlet. | 80-130       | 60             |

| Table 2. Flow rate of flue gas for the cycle. |
|-----------------------------------------------|
| Parameters    | Flow of flue gas in lakhs. (T/hr) |
| Flow gas flow | 10 (at 250MW load.)         |

The simulation was then carried in the following steps:

3.1. Main flowsheet

The main flowsheet is the first and the most important part of the simulation as all the layouts and the mappings are fed here. The requirements of the ORC cycle were taken from the model. The pump and the turbine were taken from the pressure changers tab. And the condenser and the evaporator from the exchangers tab. The flowchart was completed using the material tab which indicates how the material flows through a particular component. All the streams were labelled with a specific name or with a specific number as shown in below figure.
To obtain the work output from the turbine the work stream is selected and is placed at one side of the turbine as shown in the flowsheet. All the parameters for the cycle are displayed along with the simulation.

3.2. **The evaporator**

An evaporator is a device that turns the liquid state of the chemical substance to the vapour form. The shell and tube heat exchangers are used for this purpose. The evaporated liquid is the final product of the targeted liquid in the process. This heat exchangers can be U-tube or Straight tube. Two fluids of different temperatures flow through heat exchangers, one fluid flows through the tube side and the other flows through the shell side. The heat is transferred through one fluid to another through tube walls or vice versa. In order to transfer heat more efficiently, a large area for heat transfer should be used. In the evaporator used the flue gas is on the shell side and the organic fluid on the tube side.

3.3. **The Turbine**

The turbine is the most common expansion device used to harness power in the ORC. A turbine is a device that converts the energy from one form to another form and the energy obtained at the outlet is in the form of work done by the turbine. A turbine can have more than one stationary or rotating parts depending upon the expansion of the fluid required. The generator is coupled with turbine shaft to harness the energy from the turbine. The turbine in the ORC is generally made up of 3-5 stages. The model of the component is changed to turbine in the subpanel of turbine and the discharge pressure is selected as 2 bar. Also change the type of the turbine to isentropic turbine. The turbine shaft will have a step-up gear box along with fluid coupling.

3.4. **Condenser**

A condenser is a device used to condense a fluid by cooling it from its saturated state. The heat form one fluid is transferred to some other fluid. Condensers designs used for the cycle are of various type, in this cycle shell and tube heat exchangers can also be used as it is a closed cycle. In the condenser, the shell side will be occupied by the organic fluid and the tube side will be occupied by the cooling water from the cooling tower or vice versa. The condensate from the condenser is the given to the pump to increase the pressure of the fluid. The fluid flow inside the condenser is selected as a countercurrent flow and the stream of cooling water is fed to condenser. This cooling water can be cooled by using a cooling tower.
3.5. **Pump**

A pump is a mechanical device that uses electrical energy to transmit mechanical work, here the movement of fluid is the mechanical action. The pump used for the cycle will be a positive displacement pump. A positive displacement pump uses a fixed volume of fluid which is pumped through the discharge pipe, thus by keeping a constant discharge pressure. Here the pump will increase the pressure of the organic fluid and will again feed it to the evaporator. The specification model of the device is selected as a pump with a discharge pressure of 10 bar. Centrifugal pumps are usually used for this purpose.

3.6. **Flue Gas Stream**

The flue gas from the boiler after de-Sulphurization is given to the evaporator. The flue gas stream is the flow of the flue gas into the evaporator on the shell side. The data is fed into the software as per the given table 1, the temperature of the gas is selected as 130°C and pressure as 1atm. The flow of the flue gas is considered as 10 lakh tons per hour.

3.7. **Cooling water Stream**

Water is used as a cooling fluid in the condenser and a cooling tower setup can be used in order to remove the transferred heat from the water. The water from the cooling towers is fed to the tube or shell side of the condenser for the cooling of the organic fluid. The temperature of the cooling water was assumed to be 27°C and at pressure of 1 bar. The total flow of the cooling water through the circuit is about 30000 kg/hr. The cooling water after cooling the organic fluid comes out from the outlet with a temperature of 32°C. This fluid can be again cooled in the cooling tower of the power plant.

3.8. **Organic Fluid**

The organic fluid with a low boiling point is used in this process as the fluid can be turned into superheated vapour with small amount of heat addition of heat. The boiling point of the R245FA is about 15.3 °C (59.5 °F; 288.4 K). In case of any loss of the organic fluid the make-up fluid can be provided using a make-up tank. The fluid is assumed to have a discharge pressure of 10 bar from the pump and is fed to the evaporator with a flow rate of 3600 kg/hr.

4. **The turbine governing system**

The flue gas temperature of the power plants varies with the load i.e. the demand for the power. The lowest temperature of the flue is about 80°C and the maximum temperature ranges about 130 °C. As the temperature of the flue gas decreases the work done by the turbine will also decreases hence the generator shaft will not rotate at a constant RPM and it will not generate any power. For this purpose a step up gear box is used which will step-up the speed of the turbine shaft and this shaft will be linked to the torque converter or fluid coupling which will maintain the constant speed of the generator shaft by varying the oil level inside the coupling, for example if the turbine shaft rotates at 750 rpm at 80°C, the step up gear box will increase the speed to 2000 rpm and the fluid coupling will bring down the speed of the generator shaft to 1500rpm (Assuming the generator is a 4-pole generator.). This will ensure that generator is running even if the load varies. This system will also protect the generator from tripping at low speeds as the load decreases and also from overheating as the load increases.

5. **Results and Discussions**

The simulation for the ORC waste heat recovery was carried out and power output of the turbine shaft was 22 kW at 130°C. The speed of the turbine shaft will vary as per the blade size and the design of the turbine. It will also vary depending upon the number of stages in the turbine. The final result of the simulation in the flowsheet is given below. The cycle was also simulated with varying pumping pressure of the organic fluid. As the pumping pressure was increased the output of the turbine shaft was also increase as shown in the table below;
Table 3. Results at varying pumping pressure at 130°C.

| Pump Pressure (bar) | Work (kW) | Pump Pressure (bar) | Work (kW) |
|---------------------|-----------|---------------------|-----------|
| 5                   | 12.1462   | 13                  | 25.2694   |
| 7                   | 16.7592   | 15                  | 27.1843   |
| 9                   | 20.2292   | 17                  | 28.8151   |
| 10                  | 21.6825   | 19                  | 30.2124   |
| 11                  | 22.9929   | 20                  | 30.8345   |

Figure 2. Results of the ORC cycle at 130°C.

The graph for the pumping pressure Vs the output of the turbine shaft is given below;

Figure 3. Graph for the results at 130°C
The cycle was also tested for 120°C flue gas temperature, for the cycle to run the cooling water temperature was changed to 20°C, rest all the parameters for the cycle were the same. The main flowsheet for the cycle and the readings of the cycle with varying pumping pressure are given below,

Table 4. Results at varying pumping pressure at 120°C.

| Pump Pressure (bar) | Work (kW) | Pump Pressure (bar) | Work (kW) |
|---------------------|-----------|---------------------|-----------|
| 5                   | 6.7767    | 13.33               | 20.0587   |
| 6.67                | 10.6654   | 15                  | 21.6124   |
| 8.33                | 13.7019   | 16.67               | 22.9735   |
| 10                  | 16.1832   | 18.33               | 24.1718   |
| 11.67               | 18.2698   |                      |           |

Figure 4. Results of the ORC cycle at 120°C.

The graph for the pumping pressure Vs the output of the turbine shaft is given below;

Figure 5. Graph for the results at 120°C
The output for the cycle will vary if the working fluid in the cycle changes along with change in temperature and pressure. The output results showed a significant increase with increase in pumping pressure for both the cycles.

6. Conclusion
The waste heat recovery cycle for thermal power plants using the ORC can be implemented and can be used to generate additional power from the waste heat of the flue gas. This will also contribute to the increase in efficiency of the power plant. The turbine governing system designed for the ORC will act as a protection system for the entire cycle. The output of the turbine shaft at 130 °C was 21.68 kW at 10 bar pump pressure. The output of the turbine shaft will vary as the temperature increases or decreases, at 120°C was 16.18 kW at 10 bar pump pressure. There are several other factors which may affect the turbine shaft output such as the pumping pressure, nozzles and valves for the turbine inlet, etc. Due to the variation of the pumping pressure the output of the turbine shaft was about 30.83 kW at 20 bar pump pressure and flue gas temperature of 130°C. The cycle had a drop in the output as the temperature of the flue gas changed. The output was 24.17 kW at 20 bar pump pressure and flue gas temperature of 120°C. A suitable generator with 4 poles or 2 poles can be selected for power generation depending upon the load capacity of the turbine and fluid coupling or torque converter. This cycle will be most efficient for supercritical boilers as they have high working temperatures.

7. References
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