3-E Analysis of a 3×500 MW coal fired thermal power plant using alternative coals species

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Abstract: This article reports a study conducted to understand the influence of different coal species on the performance of a thermal power plant. The aim is to understand the difficulties in replacing an existing coal with another available species. The methodology of 3-E (Energy, Exergy and Environment) analysis has been implemented on a 3×500 MW coal fired thermal power plant located in South India. The power plant is modelled using flow sheeting software called Cycle-Tempo. Key operating parameters like temperatures, mass flow rates were compared with the operating parameters and were found to be in good agreement. Maximum exergy loss for the design coal was found to occur in the combustor (36.5%), and the least exergy loss occurred in the de-aerator (0.13%). Optimization of the power plant was carried out with the aim of maximizing the efficiency, and the energy and exergy efficiencies obtained for the power plant were 34.35% and 33.64% respectively. Simulations were carried out with six different coal species, namely (i) Raniganj, (ii) Giridih, (iii) East Bokaro, (iv) West Bokaro, (v) Wardha valley, and (vi) Korba coals and various parameters that influence the performance were examined. An environment analysis was also carried out to study the emissions caused by the different species. East Bokaro coal turned out to be the best coal from efficiency viewpoint whereas Korba coal has the lowest amount of CO₂ produced per MW power generated.

Key Words: Indian Coal, Thermal Power Plant, Exergy Analysis, Environment Analysis, Modelling

1. Introduction

Thermal power plants cater to a large portion of world’s energy requirements. Further, single large units of 2000 MW size is usually met by steam turbine based power plants. As the steam turbine power plants are limited by the laws of thermodynamics, the maximum thermal efficiency they can deliver using an optimized configuration is around 60% [1]. A basic steam turbine power plant consists of a boiler, turbine, condenser and a pump. Additional components like re-heaters and feed water heaters increase the thermal efficiency of the plant, mostly by increasing the heat added at the higher temperature [2]. A steady 2.3 % rise of power generation through coal is pointed out by Reddy et al. [3] and this is expected to trend till 2035. They have predicted a production of 15 trillion kWh energy from coal alone. In the back drop of diminishing coal reserves, a need to increase the efficiency of power plants arises. Although energy analysis is an inherent requirement during design, exergy analysis is what determines the usefulness of the available energy. Any modification in the operating parameters of the power plants, retro-fitting of new components etc. must be based on the exergy analysis rather than the energy analysis.

In two separate studies conducted [4, 5], boiler was identified as the device contributing to maximum exergy destruction. They also concluded that the efficiency increases with an increase in temperature and steam pressure, whereas the efficiency decreases with an increase in condenser pressure. Another study by Li and Liu [6] also concluded that the boiler is the source of the largest exergy destruction in their analysis of a 300 MW coal fired thermal power plant. Since boiler
comprises of combustor and heat transfer surfaces, both these devices must be addressed separately in order to improve the performance. According to a study conducted by Elhelw et al. [7], turbines follow the boiler in their contribution to exergy loss. Exergy analysis can help in identifying the magnitude and the sources of such thermodynamic inefficiencies [8]. Li et al. [9] found that thermal exergy accounts for a large fraction of the total exergy losses. Erdem et al. [10] found that increasing the boiler output pressure leads to a rise in thermal efficiency. In their article, Kler et al. [11] stated that “Reducing the waste gas temperature can lead to a reduction in temperature difference in convective heat exchangers and an increase in the area of heating surfaces”. Even when the temperature difference is very small at one end of the heat exchanger, there will still be appreciable irreversibility due to heat transfer over a finite temperature difference at other points in the heat exchanger [12]. Adibhatla and Kaushik [13] suggested a method of sliding pressure operation wherein the steam generator pressure can be varied, which could result in reduced exergy destruction. Apart from this, Vakilabadi et al. [14] suggested the regular addition of heat and water recovery systems to increase overall performance and exergy efficiency. Chauhan and Khanam [15] stated that combustion process contributes to the lion’s share of exergy destruction. Gupta and Kaushik [16] concluded that condensers are the source of least exergy loss, but maximum energy loss. Oko and Njoku [17] found out that rising ambient temperature results in the drop of exergy efficiency and power output. Fu et al. [18] found that the decrease in isentropic efficiency of a component leads to an increase in exergy destruction. Periodic cleaning and maintenance of the condenser pipes can help in increasing the efficiency of both the condenser, as well as the plant [19]. Bidabadi et al. [20] suggested that using a counter flow arrangement in the boiler, not only does the boiler efficiency increase, but the amount of pollutants produced decreases.

India relies heavily on coal as an indigenous source of energy due to the vast reserves in various parts of the country [21]. However, most Indian coal species are of low quality due to high ash content [22]. Several studies on Indian coals have been studies under different operational and configurational conditions [22-24]. It is also important to have coal flexibility in operating a power plant to tackle problems of coal mine exhaustion and also issues related to logistics. Fuel flexibility involves issues of compatibility in composition, grindability, emission and economic factors. However, the thermal performance of the power plant mostly depends on the composition and operational parameters. So, a detailed investigation of thermal performance, especially from the viewpoint of 2nd law is required. To the best of our knowledge, such a study was not carried out on Indian coals. Hence, this work aims to study the performance of an existing power plant while using six different Indian coal species. Focus is on Energy, Exergy and Environment aspects of the performance. Even though the overall power output and CO$_2$ emissions can be determined by the fuel composition and heating value, detailed component wise analysis needs to be carried out to identify and quantify the exergy destroyed. Exergy destruction can point out the process/components which need improved design for better utility. This cannot be carried out by energy analysis alone. Hence this study is necessary to evaluate the energy, exergy and environmental aspects of a thermal power plant and its ability to handle different coals.

2. Methodology

All calculations related to energy and exergy are based on the standard concepts of 1st and 2nd laws of thermodynamics. The following notations and equations have been adopted from Cengel and Boles [2]. These equations have been derived from first principles and hence are accurate.

2.1. Energy balance in a steady flow system

\[ \Sigma_{in} \dot{E} = \Sigma_{out} \dot{E} \]  \hspace{1cm} (1)

For multiple streams,
\[
\dot{Q} - \dot{W} = \sum_{\text{out}} m \left( h + \frac{v^2}{2} + gz \right) - \sum_{\text{in}} m \left( h + \frac{v^2}{2} + gz \right)
\]
(2)

For a single stream,
\[
\dot{Q} - \dot{W} = \dot{m} \left[ h_2 - h_1 + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1) \right]
\]
(3)

2.2. Exergy balance in a steady flow system

\[
\dot{X}_{\text{in}} - \dot{X}_{\text{out}} - \dot{X}_{\text{destroyed}} = 0
\]
(4)

\[
\dot{X}_{\text{heat}} = \left(1 - \frac{T_0}{T}\right) \dot{Q}
\]
(5)

\[
\dot{X}_{\text{work}} = \dot{W}_{\text{useful}}
\]
(6)

\[
\dot{X}_{\text{mass}} = \dot{m} \psi
\]
(7)

\[
\psi = (h - h_0) - T_0 (s - s_0) + \frac{v^2}{2} + gz
\]
(8)

\[
\dot{X}_{\text{destroyed}} = T_0 \dot{S}_{\text{gen}}
\]
(9)

However, the changes in kinetic and potential energies of flowing streams have been ignored in this study.

Reversible work, or the maximum possible work, in a combustion process that does not involve any work, is equal to the exergy destroyed, and can be calculated as follows:

\[
W_{\text{rev}} = \dot{X}_{\text{destroyed}} = \sum_{\text{f}} N_{\text{f}} \left( \bar{h}_f^0 + \bar{h} - \bar{h}_0 + T_0 \bar{S} \right)_{\text{f}} - \sum_{\text{p}} N_{\text{p}} \left( \bar{h}_p^0 + \bar{h} - \bar{h}_0 + T_0 \bar{S} \right)_{\text{p}}
\]
(10)

\[
\eta_I = \frac{W_{\text{useful}}}{Q_{\text{input}}}
\]
(11)

\[
\eta_{II} = \frac{W_{\text{useful}}}{W_{\text{reversible}}} = \frac{\eta_I}{\eta_{II}} = \frac{\dot{X}_{\text{recovered}}}{\dot{X}_{\text{supplied}}}
\]
(12)

The coal fired thermal power plant studied in this article consists of three turbines, a steam generator apparatus, five feed water heaters, a de-aerator and a condenser. Modelling and simulations have been carried out using Cycle-Tempo. The exergy analysis gives detailed insights on the amount of exergy lost in each apparatus. The inlet pressure values of the feed water heaters and the de-aerator were optimized in order to increase the overall efficiency of the plant. Coal samples from six different coal fields situated across India were used as fuel in the simulation, and the efficiencies were compared. Various parameters were studied and compared for each coal sample, and a detailed environmental analysis was carried out in order to come up with the best coal species.

3. Results and Discussion

Modelling of the 500 MW power plant was carried out in Cycle-Tempo. The fuel used was the design coal having a moderate carbon content of 32% and high ash content of 41%. This coal is similar to the Korba mine coal, India. Standard air was used as the source of air. The composition of fuel and air are mentioned in the Tables 1 and 2 given below. A pressure of 1 atm and a temperature of 30°C was defined as the environment conditions, which are required for carrying out the exergy analysis. The inlet pressure values of all the low-pressure feed water heaters and the de-aerator were optimized, to maximize the efficiency. The deaerator is located between the low pressure and high pressure feed water heaters and it receives steam from the intermediate pressure turbine. It performs two functions viz. removing dissolved air from the feed water, which reduces the quality of water, and preheat the feed water heater. It is an important component of a thermal power plant using steam as the working fluid.
Figure 1 shows the detailed schematic of the power plant and also the results, mostly in terms of pressure, temperature, enthalpy and mass flow rates at salient points. The following assumptions have been made:

i. All turbines operate at an isentropic efficiency of 95%.

ii. All pumps operate at an efficiency of 92%.

iii. Cooling water used in the condenser enters at 25°C and leaves at 30°C.

iv. Relative humidity of air is 50%.

v. The flue gas exits the stack at 350°C.

vi. The de-aerator is modelled as an open feed water heater, while the remaining feed water heaters are of non-contact type.

vii. Any water and steam leakages in the system are ignored.

Table 1. Composition of the design coal used

| Component | C  | H₂  | H₂O | N₂  | O₂  | S(s) | SiO₂ |
|-----------|----|-----|-----|-----|-----|------|------|
| Mass %    | 32.05 | 3.3 | 14.0 | 0.83 | 8.54 | 0.0  | 41   |

Table 2. Composition of ambient air used

| Component | Ar | C  | H₂O | O  | N₂  | O₂  |
|-----------|----|----|-----|----|-----|-----|
3.1. Validation

In the comparative study that was carried out, the temperature and mass flow rates at 10 different salient points in the power plant scheme were compared and tabulated in Table 3 below. The power output was fixed at 500 MW. From the Table 3, it can be seen that except in the Low Pressure feed water heater inlet temperature, all other temperatures and mass flow rates are around an error of 5% from the actual design conditions. The discrepancies between the design and predicted parameters could be due to the differences in the choice of pinch and approach points, turbine and pump efficiencies and also due to the leakage of steam and water in the actual power plant, which have been ignored in the simulation. Thus we were convinced that the Cycle-Tempo model is accurate enough to carry out a parametric study. Further, various parameters like inlet air temperature, cooling water temperature gain, condenser pressure and power output were varied to monitor how these changes affected the energy and exergy efficiency. The results have been displayed in the form of graphs below. These figures are meant to check if the model predicts some established results or not. Figure 2 shows the influence of inlet air temperature on thermal efficiency. It shows an increasing trend because of the increase in the average temperature of heat addition to the working fluid. Figure 3 shows the influence of condenser cooling water temp rise on efficiency. Here, we can see a slight increase in efficiency because the amount of pump work has reduced due to the reduction of cooling water required. Figure 4 shows the influence of condenser pressure on efficiency and an established result of higher efficiency at lower pressures is evident. Figure 5 shows the variation of efficiency with power output. Here, there is no variation in efficiency. This is because efficiency depends only on operating parameters and not on the output power. The mass flow rate adjusts itself to the change in the output and hence, efficiency remains constant. However, in reality, higher mass flowrates result in larger pressure drops which will result in larger pump power consumption. This emphasizes the importance of auxiliary power consumption and pressure drops, which need to be accurately estimated for precise analysis. All the arguments presented above are valid for both energy and exergy efficiencies.

| Sl no | State point        | Mass flow rate, m (kg/s) | Temperature, T (°C) | Error % | Mass flow rate | Temperature |
|-------|--------------------|--------------------------|---------------------|---------|----------------|-------------|
|       |                    | Actual                   | Cycle Tempo         | Actual  | Cycle Tempo    |             |
| 1     | Boiler outlet      | 404.72                   | 385.16              | 537     | 537            | 4.83        | 0           |
| 2     | Reheater inlet     | 361.45                   | 340.95              | 337     | 337            | 5.67        | 0           |
| 3     | LP turbine inlet   | 296.32                   | 303.48              | 309.9   | 307.61         | 2.41        | 0.73        |
| 4     | Condenser inlet    | 259.68                   | 259.70              | 46.6    | 46.32          | 0.009       | 0.6         |
| 5     | Condenser outlet   | 320.27                   | 303.48              | 46.4    | 46.32          | 5.24        | 0.17        |
| 6     | LP Heater 1 inlet  | 11.01                    | 11.81               | 72.4    | 71.05          | 7.23        | 1.86        |
| 7     | LP Heater 2 inlet  | 19.98                    | 20.75               | 147.7   | 134.3          | 3.82        | 9.07        |
| 8     | LP Heater 3        | 11.31                    | 11.21               | 208.4   | 197.01         | 0.86        | 5.46        |

Table 3. Variation in temperatures and mass flow rates
The exergy analysis was carried out using a dead state environment defined by Baehr [25]. A pressure of 1 atm and a temperature of 30°C was used as the environment condition for the exergy analysis. Exergy losses at each component of the power plant was determined through this exergy analysis. The results have been represented in the Table 4 and Sankey diagram given in figure 6.

### Table 4. Exergy loss at each component

| Sl no. | Apparatus     | Exergy loss (%) |
|--------|---------------|-----------------|
| 1      | Turbines      | 2.06            |
| 2      | Condenser     | 2.83            |
| 3      | Stack         | 6.58            |
| 4      | Combustor     | 3.65            |
| 5      | Steam generator | 15.61         |

**Figure 2.** Variation of efficiency with inlet air temperature

**Figure 3.** Variation of efficiency with gain in cooling water temperature

**Figure 4.** Variation of efficiency with condenser pressure

**Figure 5.** Variation of efficiency with power output
Figure 6. Sankey diagram representing exergy losses

The combustor was found to be the biggest source of exergy destruction, in which 36.5% of the total available exergy was lost. The steam generating apparatus including the combustor accounts for 52.11% of the total exergy loss. The least exergy loss took place in the de-aerator. The total exergy lost was found to be 66.36%. The remaining fraction of exergy is the second law efficiency or the exergy efficiency of the plant, which is 33.64%.

3.2. Simulation using different coal species

Simulations were carried out for six different coals taken from six coal fields located at various states across India. Their composition was obtained from Chandra and Chandra (2004). The composition of each coal sample is shown in Table 5 given below. In order to compare the results, the combustor outlet temperature and evaporator outlet temperature were taken as 1150°C and 1000°C respectively, for all the simulations that were carried out.

Raniganj and East Bokaro coals have high carbon content and low ash content while highest ash is seen in Korba coal. It can be inferred that the mass flow rate of flue gas and efficiencies depend on the fraction of carbon present in the fuel. Mass flow rate of the flue gas decreases with increase in the amount of carbon present in the fuel. This is because lesser carbon implies more fuel flow rate to produce the same amount of power, and hence more air and flue gas. Moreover, lesser carbon in fuel implies that other components like moisture, oxygen and nitrogen would be more, all of them being heavier than carbon. On the other hand, energy and exergy efficiencies were found to increase slightly with increase in the fraction of carbon present in the fuel. The reason for such a trend is the increase in boiler efficiency with increase in carbon content in the fuel. Hence exergy loss in the combustor is reduced.

Table 5. Composition of coal samples, mass flow rate of flue gas generated and efficiencies
3.3. Effect of combustor inlet air temperature

It can be observed from Figure 7 (a) and (b) that with increase in combustor inlet air temperature, there is an increase in both efficiencies. The reason for this trend is that a rise in air temperature results in the decrease of the amount of heat supplied in the form of fuel. Also, the total exergy at the inlet (thermo-mechanical as well as chemical exergy) is decreased. Further, there is a reduction in exergy loss at the air-preheater due to reduced temperature difference needed for heat transfer. Also, it can be seen that the Raniganj and East Bokaro coals stand apart at a higher efficiency compared to other coals, which could be due to their superior composition, i.e. carbon content.
3.3.1. Effect of combustor outlet temperature

It can be observed from Figure 8. (a) and (b) that efficiencies increase steeply with increase in combustor outlet temperature. This can be attributed to the fact that an increase in flue gas temperature at the combustor outlet leads to more heat transfer at higher temperature. This is in accordance to the 2nd law of thermodynamics. However, when the steam temperature remains the same, higher flue gas temperature will result in larger irreversibility, resulting in additional exergy destruction. Moreover, there is no appreciable difference between the various coal species as far as this result is concerned.

3.3.2. Effect of inlet steam temperature

Figure 9 shows the influence of steam turbine inlet temperature on efficiencies. A range of 500 to 700 °C has been chosen so as to cover the power plants with higher operating parameters too. However, the pressure has been kept constant, keeping the metallurgical limit in mind. With increase in steam temperature to the high-pressure turbine, an increase in efficiency was noticed. This is because, the degree of superheat is raised when steam temperature is raised, keeping the pressure constant. This influences both the power output as well as the heat input. However, the increase in the former will offset the increase in the latter resulting in an overall improvement of the power output, and hence efficiency. This is where, the choice of inlet pressure and temperature play a key role. Once again, there seems to be no influence of coal species on this result.
3.3.3. Effect of gain in cooling water temperature across condenser

Cooling water temperature rise has been varied from 5 to 25°C. This is only of academic interest as a rise of 25°C will be detrimental to the marine life living in the water body that supplies the cooling water. Also, such a high temperature rise puts additional load on the cooling tower. Moreover, the rise in cooling water temperature to 25°C implies a rise in the condenser pressure and hence temperature. This will reduce the power produced. However, an increase in efficiency is observed with increase in gain in cooling water temperature. This trend is seen in Figure 10. This could be because there is lesser exergy loss in condenser with increase in gain in cooling water temperature, as a result of reduction in the temperature difference between the exhaust cooling water and the incoming turbine exhaust system [24]. Also, the amount of cooling water needed by the condenser decreases with increase in the temperature gain. This reduces the pumping power required, resulting in a slight improvement in efficiency. In this case, the Raniganj and East Bokaro coals fare better than others, which could be attributed to lower flue gas flow rates and hence lower blower power consumption.

3.3.4. Effect of condenser pressure

The effect of condenser pressure is visualized in Figure 11(a) and (b). The chosen range of 6 to 14 kPa is typical of Indian power plants. A decrease in efficiency was observed with increase in condenser pressure. This can be attributed to the increase in mean temperature of heat rejection in the condenser as its pressure is increased. This observation is in accordance with the laws of thermodynamics. However, the amount of rise in efficiency may not be close enough to reality as the
power needed to maintain vacuum is not considered. Hence, magnitudes of efficiency found in the figure 11 are ambitious while the real figures will be slightly lower. East Bokaro and Raniganj coals show a slightly better performance compared to other species. This is in no way related to the condenser pressure and can be attributed to their generally superior composition.

![Figure 11. Variation of efficiency with condenser pressure](image)

![Figure 12. Variation of efficiency with ash content in fuel](image)

3.3.5. Effect of ash content in fuel

Out of the fuel samples considered, the coal from Korba coal field situated in Chhattisgarh had the highest fraction of ash present in it, while the coal from East Bokaro coal field located in Jharkhand had the lowest. The efficiency values obtained when each sample was used as fuel is showed in Table 5. The coal from East Bokaro coal field delivered the highest efficiency, whereas the coal from Korba coal field delivered the lowest. It can be observed from Figure.12 that efficiency reduces with increase in ash content in the fuel. This is because, higher ash coals need to be fed at a larger rate to produce the same amount of power. Therefore, the fuel and air consumption increases thereby increasing the power consumed by the fuel and air supply systems. Although not modelled in this work, more ash results in thick deposits on the heat transfer surfaces resulting in poorer heat transfer rates. Also, ash leaves the combustor as molten slag at high temperature, thereby causing a direct heat loss.

3.3.6. Effect of ambient temperature

Figure 13 shows the variation of efficiency as a function of ambient temperature. Ambient temperature influences the temperature of combustion air as well as the heat rejected at lower temperature of the cycle. The range of 25 to 50°C is chosen for this study since the lower limit is a common temperature in several parts of the world while the higher limit is often found in the desert
regions of the world. It is observed that efficiency slightly decreases with increase in ambient air temperature. This could be due to the increase of temperature of heat rejection of the cycle. It is in accordance with the laws of thermodynamics. Also, lower ambient temperature implies higher exergies of all streams. Hence, power plants in colder regions operate at a higher efficiency than those in hot regions. Here too, the Raniganj and East Bokaro coals demonstrate slightly better efficiencies which could be due to their superior quality.

![Figure 13. Variation of efficiency with ambient temperature](image)

3.4. Environment analysis

Environment analysis was carried out by analyzing the composition of the exhaust gas which enters the stack. The composition of the exhaust gas along with their respective mass fractions are mentioned in the Table 6 given below.

| Coal field | Mass fraction of gases in emission | CO₂ per MW (kg/M) |
|------------|-----------------------------------|-------------------|
|            | H₂O  N₂  O₂  Ar  CO₂  SO₂        |                   |
| Raniganj   | 0.0236628 0.7893 0.0826 0.0133 0.0909 0.0002372 | 0.33358           |
| Giridih    | 0.020661 0.7318 0.1633 0.0124 0.0714 0.000439 | 0.2628            |
| East Bokaro| 0.021962 0.7284 0.1519 0.0123 0.085 0.000438 | 0.31188           |
| West Bokaro| 0.018281 0.7325 0.1631 0.0124 0.0735 0.000219 | 0.27117           |
The emission of \( \text{CO}_2 \) gas is the least when coal from Korba coal field is used as fuel. Hence from an emission point of view, the use of this fuel would cause the least harm to the environment.

4. Conclusions

Efficiency was found to increase with increase in parameters like inlet air temperature to the combustor, overall power output, gain in cooling water temperature in the condenser, combustor outlet temperature and steam inlet temperature at the high pressure turbine. Efficiency decreased with increase in condenser pressure, ash content in the fuel and ambient temperature. Exergy analysis shows that highest exergy loss takes place in the combustor (~37%), which is followed by the steam generator (~16%). Since, boiler is a combination of combustor and steam generator, this result is in general agreement with literature. The least exergy loss took place in the de-aerator (~0.13%). The overall exergy efficiency of the power plant was found to be 33.64%. Fuel with higher carbon content and low ash content will give higher efficiency. Among the fuel species studied, coal from East Bokaro coal mine located in Jharkhand produced the highest efficiency.

5. Nomenclature

| Symbol | Name                                      |
|--------|-------------------------------------------|
| \( \dot{E} \) | Rate of energy transfer (power), kW       |
| \( g \) | Acceleration due to gravity=9.81 m/s²    |
| \( h \) | Enthalpy, kJ/kg                           |
| \( h_0 \) | Enthalpy at dead state, kJ/kg             |
| \( m \) | Mass flow rate, kg/s                      |
| \( Q \) | Rate of heat transfer, kW                 |
| \( s \) | Entropy, kJ/kg-K                          |
| \( s_0 \) | Entropy at the dead state, kJ/kg-K        |
| \( T \) | Temperature, K                            |
| \( T_0 \) | Temperature at the dead state, K          |
| \( V \) | Velocity, m/s                             |
| \( W \) | Rate of work (power), kW                  |
| \( \dot{X} \) | Rate of Exergy Transfer, kW              |
| \( z \) | Height, m                                 |
| \( \eta \) | Efficiency                               |
| \( \eta_I \) | First law efficiency or Thermal efficiency |
Second law efficiency

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