International Journal of Scientific & Engineering Research, Volume 6, Issue 3, March-2015
ISSN 2229-5518

Optimizing Performance and Fuel Economy of Power Generation using Model Based Design

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Abstract— The energy supply to demand is narrowing down day by day around the world, the growing demand of power has made the power plants of scientific interest, but most of the power plants are designed by the energetic performance criteria. With introduction of electricity act 2003, power sector has been opened to private players. Many private players have added huge capacity of power generation. This has resulted in very competitive environment in the power sector. So to run the business, the cost of generation has to be less than cost of selling power. Hence In order to sustain, in this competitive environment it becomes imperative to focus on reduction in the generation cost. And ultimately fuel cost. With this background the project on Fuel cost optimization is taken. Fuel cost is governed by many variables. To optimize fuel cost, optimization of these variables is essential. For this purpose optimization model for each major factor is developed. These models are developed using Microsoft Visual Basic software. All the variables that affect the fuel cost are analysed. Seven different types of coal were taken for analysis and their suitability, costs, efficiency, Heat rate were obtained. A case study was taken keeping blending ratio as constraint and analysis of the seven types of coal was carried out and optimized result was obtained.title.

Index Terms— Blending, Coal, Efficiency, Fuel cost, Heat rate, Optimization.

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1 INTRODUCTION

COAL has long been the major fossil fuel used to produce electricity. However, coal-fired electric power plants are one of the largest sources of air pollution, with greenhouse gas (GHG) emissions from burning of fossil fuels believed to be the major contributor to global climate change. The overall efficiency of a power plant encompasses the efficiency of the various components of a generating unit. Minimizing heat losses is the greatest factor affecting the loss of coal fired power plants (CFPP) efficiency, and there are many areas of potential heat losses in a power plant. The options most often considered for increasing the efficiency of CFPPs include equipment refurbishment, plant upgrades, and improved operations and maintenance schedules.

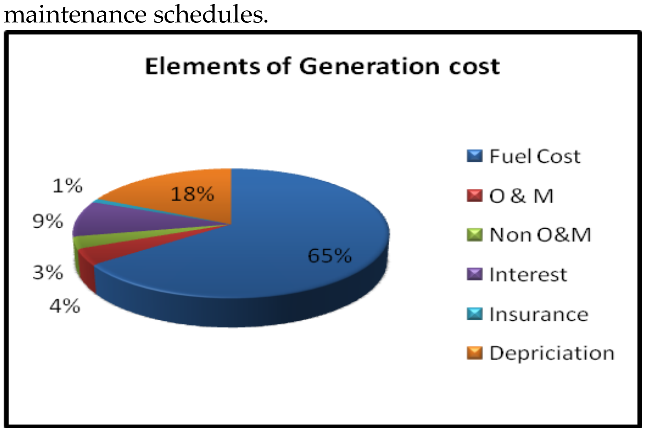

Fig1: Elements of generation cost

Overall optimization of a coal-fired power plant is a highly complex process. The target for optimal performance includes maximum thermal efficiency, lowest possible emissions, lowest possible cost, readily marketable By-products and maximum system availability for power generation.

In order to understand the factors influencing the cost of generation typical elements of cost of generation were collected and are depicted in the pie chart as shown in Fig1. The major component in generation cost is fuel cost. As discussed about it in competitive environment, it is important to explore all methods to reduce fuel cost.

Nomenclature

F / A = Fuel–air ratio used in combustion process
T = Temperature (°C)
Q = Quantity of steam generated (kg/hr)
q = Quantity of fuel used per hour (kg/hr)
GCV = Gross calorific value of the fuel (kCal/kg)
h = Enthalpy (kCal/kg)
T_f = Flue gas temperature (^{0}C)
T_a = Ambient temperature (^{0}C)
C_p = Specific heat (kCal/kg)
m = Mass of dry flue gas in kg/kg of fuel
HF = Humidity factor

Aljundi [1] carried out component wise modelling and a detailed break-up of energy and energy losses for a steam power plant in Jordan. He proposed that individual components had to be analysed and their losses were to be minimised so as to collectively improve the performance of the

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entire power plant. Naterer et al. [2] analysed the coal-fired thermal power plant with measured boiler and turbine losses. Their works concentrated on the loss of energy in boiler and turbine only and ways to reduce them. Reducing the losses meant increasing the efficiency and thus reducing the generation cost. Ganapathy et al. [3] determined the energy loss of the individual components of lignite fired thermal power plant. Zubair and Habib [4] performed second law based thermodynamic analysis of the regenerative-reheat Rankine cycle power plant. Reddy and Butcher [5] analysed waste heat recovery based power generation system based on second law of thermodynamics. Bilgen [6] presented the exergetic and engineering analyses as well as simulation of gas turbine-based cogeneration plants consisting of a gas turbine, heat recovery steam generator and steam turbine.

Amit [7] showed that power plant optimization can be carried out by using online optimization systems which provide real time analysis of various parameters and their deviation from the design. These systems were able to detect the losses incurred by the plant due to fouling in components, leakages, improper operation, incorrect fuel to air ratio and change in coal composition. The new generation plants have the better edge in adopting the optimizing techniques based on software solution that utilize the existing instrumentation to tune the plant parameters.

Keeping in view the facts stated above, it can be expected that performing an analysis based on the performance criteria will be meaningful for performance comparisons, assessments and improvement for thermal power plants. Plant optimization is now an integral part of the process industry partly due to government and environment regulations and also largely due to improvements that can be realized in terms of monetary benefits. To meet the requirements of various parameters such as GCV of coal, coal quality, moisture, heat rates, emissions etc on important process parameters such as boiler efficiency, generation cost, power sale etc, a decision making model becomes necessary which can help in optimizing the input parametrs so as to get a desired output with improved efficiency.

The work presented in this paper examines the impact of coal quality and blending ratios on the fuel cost in a thermal power plant.

2 Procedure for Calculating Fuel Cost

For the purpose of optimizing the fuel cost a sensitivity analysis of all the parameters was carried out. Fig2 shows the cost optimization flow chart. The work was divided into five major parts, namely

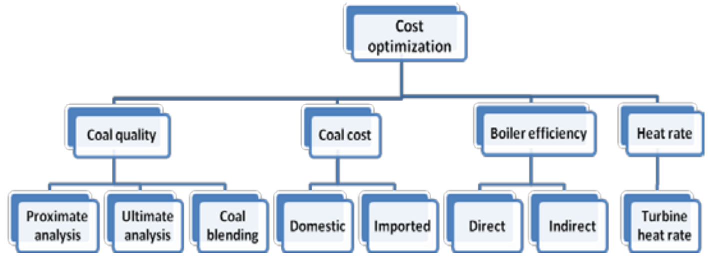

Fig2: Cost optimization flow chart

i. Identification of variables
ii. Blending Economics
iii. Models for each variables-Fuel cost Optimization
iv. Methods to Reduce Fuel Cost
v. Conclusion

2.1 Identification of Variables

The study was carried out by adopting four main variables that affected the plant performance.

2.1.1 Coal Quality:

Here two types of coal analysis were carried out and the properties of coal were found out. The two types of coal analysis are:

i. Proximate analysis
ii. Ultimate analysis

Variables under proximate analysis are:

a) Gross Calorific Value
b) Fixed Carbon
c) Total Moisture
d) Volatile Matter
e) Ash Percentage

Variables under ultimate analysis are:

a) Hydrogen
b) Sulphur Content
c) Nitrogen
d) Oxygen
e) Carbon

The formula adopted for converting proximate analysis into ultimate analysis is as shown in equations 1, 2 and 3.

$$\%C = 0.97C + 0.7\left(VM + 0.1A\right) - M\ \left(0.6 - 0.01M\right) \quad -eq(1)$$

$$\%H_2 = 0.036C + 0.086\left(VM - 0.1\ A\right) - 0.0035M^2\left(1 - 0.02M\right) - eq(2)$$

$$\%N_2 = 2.1 - 0.020\,VM \quad -eq(3)$$

Where,
C = % of fixed carbon
A = % of Ash
VM = % of Volatile matter
M = % of Moisture

2.1.2 Coal Cost

The coal cost mainly consists of the following components.

a) Basic cost
b) Freight costs
c) Loading/ Unloading charges
d) Transit loss
e) Windage loss

The components that come under the basic cost are,

- Base Price
- Royalty
- Clean energy cess
- Stowing excise duties
- CST
- Excise duty
- Sizing charges
- Environment

The components under Freight cost are:

- Basic freight
- Development charges
- Development surcharges
- Service tax

Total coal cost therefore is the sum of basic cost, freight cost, lloading / unloading charges, transit loss and Windage loss

2.1.3 Boiler efficiency

In order to calculate the boiler efficiency by indirect method, all the losses that occur in the boiler must be established. However these losses are in turn related to the amount of fuel burnt. Hence it is easy to compare the performance of various boilers with different ratings.

There are two methods to find out boiler efficiency. They are the direct method and the indirect method. In the direct method boiler efficiency is calculated with the help of formula given in equation 4.

Boiler efficiency = $Heat\ output / Heat\ input$

$$\eta_b = \frac{Q_o}{Q_i} = \frac{h_g - h_f}{q \times c.v} \times 100 --- eq(4)$$

Where q is the fuel consumption and cv is the calorific value of the fuel.

In the Indirect method efficiency is measured by measuring all the losses occurring in the boiler. The following losses were applicable to all the fuel used, such as solid, liquid or gas fired boiler.

L1 – loss due to dry flue gas
L2 – loss due to hydrogen in fuel
L3 – loss due to moisture in fuel
L4 – loss due to moisture in air
L5 – loss due to incomplete combustion
L6 – loss due to un-burnt fuel in fly ash
L7 – loss due to un-burnt fuel in bottom ash
L8 – loss due to radiation and convection
(Surface loss)

In the above listed losses, loss due to moisture in fuel and the loss due to combustion of hydrogen are dependent on the fuel, and cannot be controlled by design.

Boiler efficiency $\eta = 100 - Total$ percentage $losses$

$$\eta_b = 100 - (L1 + L2 + L3 + L4 + L5 + L6 + L7 + L8)$$

The following procedure is adopted in the study for calculating the losses.

Step1.Theoretical (stoichiometric) air requirement

Theoretical air requirement (TA) =
$(11.6C + 34.8(H2 - O2/8) + 4.35S)/100$ kg/kg of fuel

Step2. Excess air requirement
% excess air requirement (EA) = $(O2\% / (21 - O2\%)) X 100$

Step3. Actual air (total air) requirement

Actual air (total air) requirement (AAR) = theoretical air x $(1 + EA/100)$ $kg\ of\ air/ kg\ of\ fuel$

Step4: Estimation of heat losses:

L1 - Dry flue gas loss is given as,

$$L_1 = \frac{m\,C_p\,(T_f - T_a)}{GCV\ of\ Fuel} \times 100$$

And this is equal to mass of CO_2 +mass of SO_2 + mass of N_2 + mass of O_2 (water vapor mass is neglected)

$$= \left(\frac{C}{100} \times \frac{44}{12}\right) + \left(\frac{s}{100} \times \frac{64}{32}\right) + \left(AAR \times \frac{77}{100}\right) + \left((AAR - T_a) \times \frac{23}{100}\right)$$

L2 - Loss due to hydrogen in fuel is given as,

$$L_2 = \frac{9\,X\,H_2\left[584 + C_p\left(T_f - T_a\right)\right]}{GCV\ of\ Fuel} \times 100$$

L3 - Heat loss due to moisture present in fuel is given as,

$$L_3 = \frac{M\left[584 + C_p\left(T_f - T_a\right)\right]}{GCV\ of\ Fuel} \times 100$$

L4 - Heat loss due to moisture present in air is calculated as follows.

$$L_4 = \frac{AAS \times HF \times C_p\left(T_f - T_a\right)}{GCV\ of\ Fuel} 100$$

Where c_p is the specific heat of super-heated steam which is = 0.45 Kcal/kg°C.

L5 - Heat loss due to incomplete combustion is given as,

$$L_5 = \frac{\%CO \times C}{\%CO + \%CO_2} \times \frac{5744}{GCV\ of\ \ fuel} \times 100$$

L6 - Heat loss due to radiation and convection is given as,

$$L_6 = 0.548\left[\left(\frac{T_s}{55.55}\right)^4 - \left(\frac{T_a}{55.55}\right)^4\right]$$

$$+ 1.957 \times (T_s - T_a)^{1.25} \times \sqrt{\frac{196.85\ V_m + 68.9}{68.9}}$$

L7 - Heat loss due to unburnt in fly ash is given as,

$$L_7 = \frac{Total\ ash\ collected\ /\ kg\ of\ fuel\ burnt \times GCV\ of\ fly\,ash}{GCV\ of\ fuel} \times 100$$

L8 - Heat loss due to unburnt ash can be given as,

$$L_8 = \frac{Total\ ash\ collected\ \ per\ kg\ of\ fuel\ burnt \times GCV\ of\ bottom\ ash}{GCV\ of\ fuel} \times 100$$

The sum of all the heat loss is obtained by adding the percentage losses L_1 to L_8.

The boiler efficiency, η_b is then calculated as, 100 − (% total losses)

2.1.4 HEAT RATE CALCULATION

The heat rate of a plant is calculated as the amount of fuel energy needed to produce 1 kWh of net electrical energy output. There are two types of heat rate that are calculated.

i. Turbine Heat Rate
ii. Unit Heat Rate

$$Unit\ heat\ rate = \frac{Turbine\ heat\ rate}{Boiler\ efficiency} \times 100$$

Other important performance parameters involved is the specific coal consumption which is given as,

The Overall coal consumption is the specific coal consumption times the total power generation.
The cost of fuel per unit is calculated as,
Cost of fuel per unit = (Overall coal consumption x cost of coal) /generation

3 METHODOLOGY

Seven different types of imported coal were taken in to study named from x1 to x7 and their properties along with their costs were collected for analysis.
Cost optimization analysis was carried out taking into account the following factors.

i. Coal Suitability
ii. Cost of fuel, efficiencies and Heat rate
iii. Blending Ratio

3.1 COAL SUITABILITY CHECK:

Suitability check is carried out mainly because of the fact that the technical specifications of imported coal is not in conjunction with the technical specification of some of the boiler design due to which it is not possible to use large quantity of imported coal. By varying the blending ratio, suitability check was carried out using visual basic. Table 1 shows the various types of coal and their properties:

Table 1. Various types of imported coal and their properties

Coal Type	GCV	Sulphur	Ash	TM	IM	VM	FC	AFT
Domestic	4049	0.5	35.03	9.33	3.28	25.07	30.49	1050
X1	5900	1.60%	7%	16%		35-45%	35.4	1050-1250
X2	6500	3.50%	10%	11%	5-8%	43%	32.5	1250
X3	6000	1.70%	6%	17%	12%	42%	33.3	1250
X4	5400	1.00%	16%	18%	13%	35-45%	25	1100
X5	5900	3.40%	17%	11%	5.73 %	40%	28.6	1200
X6	5900	3.40%	17%	11%	6%	38-42%	30.6	1150
X7	5700	2.30%	7%	19%	12%	38-42%	31.7	1150

ISSN 2229-5518

The range for suitability of the parameters is specified and analysis is carried out. Table 2 shows the range for suitability check.

Table2: Range for suitability

Parameters	High	Low
Total Moisture	16	
Volatile Matter	30	22
ASH	38	
GCV	4500	4000
Ash Fusion Temp	1375	1000

Table 3 shows the analysis for the coal suitability of one of the types of imported coal. The table shows the properties and suitability of the coal by varying the blending ratios from 100-0 to 70-30.

Table3: Coal suitability analysis

X1	Coal Properties		TM	VM	AFT	Ash	GCV	Suitability
Rated Coal	Lower			22	1000		4000	
	Upper		16	30	1375	38	4500	
Blended Coal	Domestic	Imported						
	100	0	9.33	25.07	1050	35.03	3950	Not Suitable
	95	5	9.66	25.82	1055	33.63	4047	Suitable
	90	10	10.00	26.56	1060	32.23	4145	Suitable
	85	15	10.33	27.31	1065	30.83	4242	Suitable
	80	20	10.66	28.06	1070	29.42	4340	Suitable
	75	25	11.00	28.80	1075	28.02	4437	Suitable
	70	30	11.33	29.55	1080	26.62	4535	Not Suitable

3.2 Analysis of costs, efficiencies and Heat rate:

The second step of analysis was to compare the boiler efficiency, generation cost, sale cost, unit heat rate and coal consumption of all the seven types of coal at various blending ratios. The properties were simulated in visual basic and the results were obtained and are tabulated as shown in table 4.

Table4: Comparison of efficiencies

Type	X1					
Domestic	Imported	Boiler η	Unit Heat Rate	Generation Cost	Sale Cost	Coal Consumption
100	0	87.020	2197	1.251	1.481	168
95	5	87.050	2196	1.336	1.566	163
90	10	87.150	2194	1.431	1.660	160
85	15	87.160	2194	1.511	1.742	156
80	20	87.180	2193	1.586	1.817	152
75	25	87.220	2192	1.666	1.898	149
70	30	87.210	2192	1.742	1.973	146

3.3 Blending Ratio Constraint:

Blending ratio was kept constraint at 80 -20 and the efficiencies and costs of all types of coal were analysed. Coal Type X6 was found to be the most efficient and cost saving composition. Table 5 shows the result for seven different types of coal compositions.

Table 5. Cost analysis keeping Blending ratio constraint

Blending Ratio Constraint						
Domestic	80	Imported	20			
Coal Type	Boiler η	Unit Heat Rate	Generation Cost	Sale Cost	Coal Consumption	Suitability
X1	87.180	2193	1.586	1.817	152	Suitable
X2	87.460	2186	1.572	1.802	148	Suitable
X3	87.140	2194	1.605	1.836	152	Suitable
X4	87.110	2195	1.608	1.840	156	Suitable
X5	87.430	2187	1.564	1.795	152	Suitable
X6	87.510	2185	1.559	1.790	152	Suitable
X7	87.100	2195	1.579	1.811	154	Suitable

4 Results and Discussion

A 500 MW plant was taken for study and from the model developed in visual basic software several data were collected and simulated and the results were compared. The properties of seven different types of coal and their costs were taken as input parameters and were simulated in the model. Fig. 3 shows the graph indicating the comparison of generation cost vs selling price and a trend of boiler efficiency is also depicted for all the seven types of coal

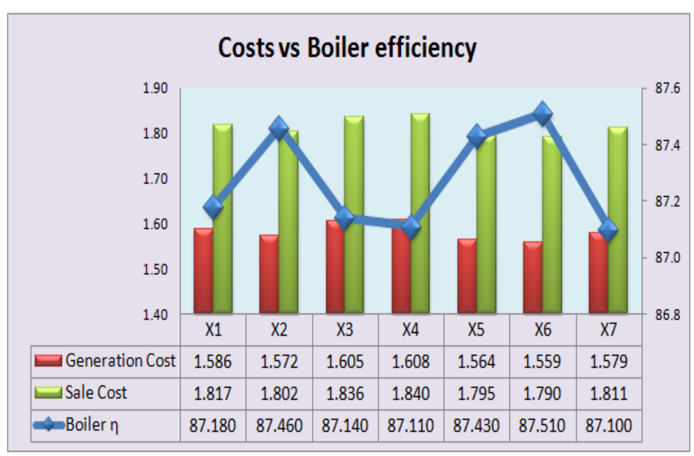

Fig3: Costs vs Boiler efficiency

Based on the analysis that was carried out, coal type X6 had the least fuel cost. A comparison of coal composition X6 with coal composition X1 is shown in table 6.

Table6: Savings shown in terms of monetary benefits

Factors	Unit	Amount
Per Unit Savings	Rs	0.027
Daily Generation	Units	1,44,00,000
Daily Savings	Rs	3,88,800
Monthly Savings	Rs	1,16,64,000
Yearly Savings	Rs	13,99,68,000

5 Conclusion

Plant optimization is now an integral part of the process industry mainly due to improvements that can be realized in terms of monetary benefits. Fuel cost can be optimized using various methods and the model presented is one such statistical tool which can guide the user in taking decisions that are optimal for the plant performance as well as fuel economy. Use of imported coal, Variation in blending ratios, improving operational efficiencies can contribute to the optimization of Fuel Cost. We can also conclude that Cost optimization leads to savings in energy consumption, reduction in auxiliary power and also reduction in emissions, thus contributing to overall optimization of the plant.

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