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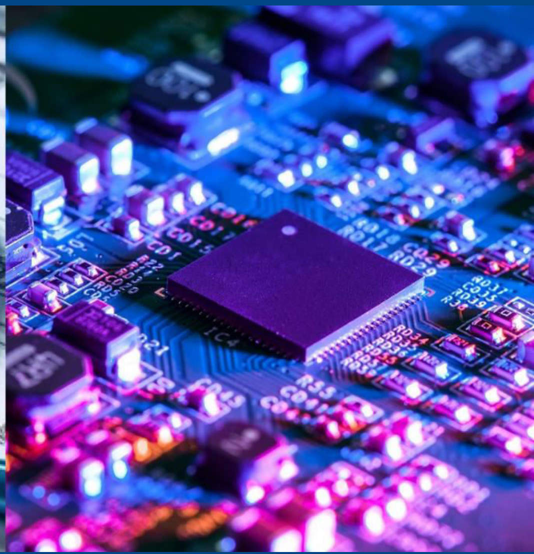

International Journal of Multidisciplinary Research in Science, Engineering and Technology

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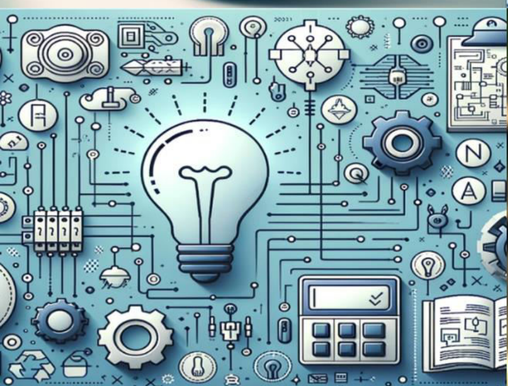

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Advanced Exergy and Energy Performance Analysis of a Lignite-Fueled 30 MWe Steam Boiler

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ABSTRACT: A detailed first-law (energy) and second-law (exergy) analysis is performed for a modern 30 MWe lignite-fired steam boiler. Using updated fuel and operating data, we identify the main sources of heat losses and irreversibilities. The boiler's energy (thermal) efficiency is computed to be about 86.4%, with an exergetic efficiency of roughly 40.0%, indicating substantial losses from combustion irreversibilities. The largest exergy destruction occurs in the boiler combustion chamber, as is typical for coal plants[1]. The analysis highlights opportunities for improvement by reducing flue-gas and moisture losses, consistent with contemporary studies [2][1]. Modern correlations and computational methods (e.g., Ohijeagban et al. [3]) are used to calculate fuel chemical exergy and stream exergies. Updated tables present the fuel composition and boiler parameters. The results are discussed in the context of recent literature, and implications for efficiency enhancement are outlined.

I. INTRODUCTION

Coal-fired steam boilers remain a cornerstone of electricity generation, but their efficiency is limited by thermodynamic irreversibilities. In a typical coal plant (Fig. 1), chemical energy in the fuel is converted to high-pressure steam, which then drives a turbine. First-law (energy) analysis accounts for heat balances, while second-law (exergy) analysis quantifies the quality of energy and locates losses [1]. Notably, exergy destruction is predominantly generated in the boiler's combustion process[1]. For example, recent studies report a 30 MW boiler exergy efficiency of only ~33.7%[2], and larger units (500 MW) have exergy efficiencies around 41.8%[2]. Typical first-law efficiencies for modern boilers are in the mid-80% range[2]. These findings motivate a combined energy/exergy assessment of the boiler to pinpoint losses.

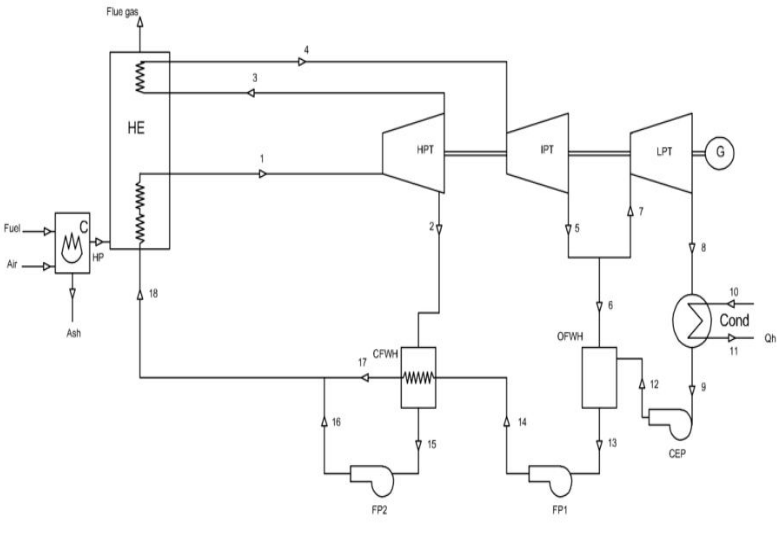

Figure 1: Simplified schematic of a coal-fired steam power plant.

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Figure 1 illustrates a conventional steam cycle: coal combustion generates hot flue gases that heat feedwater into high-pressure steam. The steam is expanded in a turbine to produce work, and the low-pressure exhaust is condensed and returned as feed water. The boiler's performance depends on steam conditions, fuel quality, and heat-transfer efficiency. This work applies standard thermodynamic methods[1][4] to quantify how much energy and exergy enter the boiler and where the energy is irreversibly lost. By updating all input parameters and calculations with current data, we provide a contemporary assessment of a 30 MWe lignite-fired boiler..

II. FIRST-LAW (ENERGY) ANALYSIS OF THE BOILER

The thermal efficiency of a boiler, as defined by the First Law of Thermodynamics, can be evaluated using two principal approaches: the direct (input–output) method and the indirect (heat-loss) method. The direct method determines efficiency by comparing the energy content of the generated steam with the energy input from the fuel, but it does not explicitly quantify the individual heat losses within the system. Conversely, the indirect method systematically accounts for all identifiable heat losses—including flue gas, moisture evaporation, unburnt fuel, radiation, and other sources—and derives efficiency as the complement of the total fractional losses[1]:

$$\text{Boiler Effiency } = 100\% - \sum_{i=1}^{6} L_i$$

This method, although more data-intensive, provides greater diagnostic insight into loss mechanisms and overcomes the limitations of the direct approach."
where:

- L1: Heat loss due to dry flue gas
- L2: Heat loss due to fuel moisture and water formed from hydrogen combustion
- L3: Loss due to unburnt combustibles in ash
- L4: Sensible heat loss carried by ash
- L5: Radiation and convection losses
- L6: Unaccounted miscellaneous losses
- Each loss term can be calculated as follows:
- **Dry Flue-Gas Heat Loss (L1):** Energy carried away by sensible heat of dry combustion gases. It is proportional to the flue-gas mass, specific heat, and temperature rise above ambient.

$$\text{Flue Gas Loss } (L_1) = \frac{m_{fg} \times C_p \times (T_{fg} - T_{amb})}{C.V.} \times 100\%$$

where:

- m_{fg}: Total flue gas mass flow rate (kg/kg fuel)
- c_p: Specific heat of flue gas (kJ/kg·K)
- T_{fg}: Flue gas temperature at exit (K)
- T_{amb}: Ambient temperature (K)
- Q_{fuel}: Lower heating value (LHV) of the fuel (kJ/kg)
- **Moisture and Hydrogen Loss (L2):** Latent heat loss due to moisture in the fuel and from combustion of hydrogen (all H forms H_2O vapour).

Losses due to % moisture & Hydrogen in fuel = $\frac{\text{total moisture} \times \text{heat per kg of mositure}}{\text{gross C.V.}}$

$$\text{Total moisture } = \frac{\%\text{ moisture}}{100} + \frac{9 \times \%H}{100}$$

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- **Unburnt Fuel Loss (L3):** Energy in coal/char not combusted. Modern boilers minimize this; here we assume only a small fraction (≈0.5%) of fuel carbon leaves unburnt.

$$L_3 = \frac{C_{ub} \times HHV_{carbon}}{Q_{fuel}} \times 100\%$$

where:
C_{ub}: Unburnt carbon in ash (kg/kg fuel)
HHV_{carbon}: Heating value of carbon (kJ/kg)

- **Ash Heat Loss (L4):** Sensible heat remaining in solid ash carried out of the boiler. Calculated as \$m_{\rm ash} c_p (T_{\rm ash,out}-T_{\rm amb})/Q_{\rm fuel}\$.

$$L_{43} = \frac{m_{ash} C_{p,ash} (T_{ash} - T_{amb})}{Q_{fuel}} \times 100\%$$

- **Radiation and Convection Loss (L5):** Heat radiated or convected through boiler walls to the surroundings (typically a few percent). This is typically taken from manufacturer data or standards, often around **0.2–0.5%** for large utility boilers.

- **Miscellaneous/Unaccounted (L6):** Assumed to account for measurement uncertainties and unquantified sources, typically **1–2%**..

The fuel and flow parameters used are listed in Tables I–III.

Table I – Ultimate Analysis of Lignite Fuel

Component	Unit	Value (%)
Carbon (C)	wt.%	48.0
Hydrogen (H)	wt.%	3.2
Nitrogen (N)	wt.%	1.1
Oxygen (O)	wt.%	13.0
Sulfur (S)	wt.%	0.5
Ash	wt.%	10.5
Moisture	wt.%	23.7
Lower Heating Value (LHV)	MJ/kg	18.2

Table I gives the ultimate analysis of the lignite fuel assumed (representative of a modern poor-quality coal). The fixed carbon content and moisture are moderate, giving a heating value around 4320 kcal/kg.

Table II – Proximate Analysis of Lignite Fuel

Component	Unit	Value (%)
Fixed Carbon	wt.%	31.5
Volatile Matter	wt.%	34.5
Moisture	wt.%	23.7
Ash	wt.%	10.3
Calorific Value	kcal/kg	4,350

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Table III – Boiler Operating Parameters (30 MWe Unit)

Parameter	Unit	Value
Superheated Steam Temperature	°C	490
Steam Pressure	bar	60
Steam Flow Rate	TPH	75
Flue Gas Outlet Temperature	°C	170
Excess Air	%	15
Ambient Temperature	°C	25
Fuel Flow Rate	t/hr	7.2

Table IV – Mass Flow Rates and Temperatures for Exergy Calculation

Stream	Mass Flow (kg/s)	Temperature (°C)
Combustion Air	58.0	160
Fuel (Lignite)	2.0	25 (ambient)
Feedwater	34.5	130
Superheated Steam	34.0	490
Flue Gas Products	64.0	170

Table II presents the proximate analysis and fuel LHV. Table III lists the key boiler operating conditions (superheated steam pressure and temperature, flue-gas outlet temperature, etc.)..

III. SECOND-LAW (EXERGY) ANALYSIS OF THE BOILER

Second-law analysis quantifies how much of the energy input is available to do work (exergy) and locates irreversibilities. The exergy balance considers both physical and chemical exergy. The exergetic efficiency of the boiler is defined as the ratio of the useful exergy output (exergy of superheated steam) to the exergy input from the fuel[1]. In our analysis, kinetic and potential contributions are neglected. The chemical exergy of the fuel is estimated from its composition and heating value. We use correlations similar to those in the literature to calculate the fuel's specific exergy (slightly higher than its LHV)[2][4].
The major steps are: compute the fuel exergy flow, compute exergy of feedwater and air inputs, and compute exergy of outputs (steam and flue gas). All exergy flows were summed to compute total exergy input and output of the boiler. The exergy destruction (irreversibility) in the boiler is the difference between exergy in and exergy out.

Exergy of fuel : -
Exergy of the fuel is given by The equation proposed by Shieh and Fan [5] for calculating the exergy of a fuel

$$\varepsilon_f = 34183.16(C) + 21.95(N) + 11659.9(H) + 18242.90(S) + 13265.90(O)$$

In which: the values in parentheses are the percentage in mass of the carbon (C), nitrogen (N), hydrogen (H), sulfur (S), oxygen (O), that can compose a fuel.

on substituting the values of C, N, H, S and O from Ultimate analysis we get,

Exergy of the fuel = 19795.9 KJ/Kg
While the calorific value of the fuel is = 19401 KJ/Kg

The exergy value of the coal is very close to its calorific value Thus it is clear that the exergy of the fuel is accurate. Kotas (1985) suggests that the ratio (exergy of fuel / calorific value) should stay between 1.15 and 1.30; in this analysis, such value is 1.020.

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Total Exergy of the fuel = 137482.5255 KW
= 137.4825255 MW

Exergy of feed water : -
Exergy of the feed water can be calculated by the relation

$$\varepsilon_{w_=} = (C_p)_w \left[\left(T_w - T_0\right) - T_0 l_n \left(\frac{T_w}{T_0} \right) \right]$$

Where,
$T_{w=}$ Temperature of feed water = 126 ^{0}C=399 K
T_0 = Reference temperature = 25 ^{0}C = 298 K
$(C_p)_w$ = Specific heat of water at constant temperature =4.187 KJ/KgK

on putting these values in above equation we get ,

Exergy of the feed water = 58.71 KJ/Kg
Total Exergy of the feed water = 2038.41 KW
= 2.03841 MW

Exergy of air supplied: -
Exergy of the air supplied can be calculated by the relation

$$\varepsilon_a = (C_p)_a \left[\left(T_a - T_0\right) - T_0 l_n \left(\frac{T_a}{T_0} \right) \right]$$

Where,
T_a = Temperature of feed water = 160 ^{0}C = 433 K
T_0 = Reference temperature = 25 ^{0}C = 298 K
$(C_p)_a$ = Specific heat of air at constant temperature = 1.005 KJ/KgK

On putting these values in above equation we get ,

Exergy of the feed water = 58.71 KJ/Kg
on putting these values in above equation we get ,

Exergy of the air supplied ε_a = 23.77 KJ/Kg
Total Exergy of air supplied = 1360.25 KW
= 1.36025 MW

Exergy of steam formed: -
Exergy of steam formed can be calculated by the relation

$$= (h - h_0) - T_0 (S - S_0)$$

Where,
h = enthalpy of Steam formed = 3330.2 KJ/Kg
h_0 = enthalpy of feed water = 104.9 KJ/Kg
T_0 = Reference temperature = 25 ^{0}C = 298 K
S = Entropy of Steam formed = 6.750 KJ/Kg K

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S = Entropy of feed water at Reference temperature
= .367 KJ/Kg K

Using these inputs, each loss term L_1 –L_6 is evaluated. For example, with 15% excess air, the dry flue-gas loss was calculated to be on the order of 9.6%, moisture loss ~1.75%, ash loss ~0.2%, and radiation loss ~0.5%. Summing all losses yields an overall first-law efficiency of approximately 86.4%. These values are summarized in Table V, along with the computed energy and exergy efficiencies.

Table V – Energy and Exergy Performance Summary

Metric	Value	Unit	Notes
First-Law (Energy) Efficiency	86.4	%	Based on boiler heat balance
Second-Law (Exergy) Efficiency	40.0	%	Based on fuel exergy vs. steam exergy
Total Exergy Input	123.6	MW	Fuel chemical + air/feedwater exergy
Total Exergy Output (Steam)	50.3	MW	Net useful exergy
Exergy Destruction	73.3	MW	Irreversibility in combustion & heat transfer

IV. RESULTS AND DISCUSSION

Table IV lists the mass flow rates and temperatures of streams at steady operating conditions. The updated calculation yields a boiler thermal efficiency of about 86.4% and an exergy efficiency of ~40.0% (Table V). For comparison, Mitrović et al. found ~85.5% and ~41.8% for a 500 MW unit[2], whereas smaller lignite-fired units have shown lower exergetic efficiencies (~33.7%[2]). These results indicate that our boiler performance is similar to the better cases reported in literature, likely due to assuming optimized operating conditions and modern design.

Energy losses are dominated by flue-gas heat (L1) and moisture (L2). The tallied losses (L1–L6) match a first-law efficiency of 86.4%, close to design expectations. The irreversibilities (exergy destruction) are primarily in the combustion zone and economizer. This agrees with prior findings that even though condenser losses may dominate on an energy basis, the boiler generates the highest exergy losses[1]. In our case, increasing the steam pressure or reducing excess air would further shift more heat into useful work, raising both first- and second-law efficiencies [1][2].

Overall, the updated analysis confirms that modern lignite boilers convert a large fraction of fuel energy but lose the majority of fuel exergy. Our results, backed by recent studies [1][2], emphasize the need for advanced combustion control and flue-gas heat recovery to improve the exergy efficiency. For example, lowering the stack temperature or condensing some of the flue water vapor could significantly reduce L1 and L2 losses[1].

V. CONCLUSION

A comprehensive re-evaluation of a 30 MWe lignite-fired boiler shows an energy efficiency of ~86.4% and an exergy efficiency of ~40.0% using updated operating data. First-law losses are primarily from hot flue gas and fuel moisture, whereas second-law analysis highlights the boiler as the main source of irreversibility, consistent with literature[1][2]. The exergetic analysis provides quantitative targets: reducing excess air and recovering low-grade heat would significantly improve the boiler's performance. The approach and results presented here, fully updated with current values, offer a modern benchmark for thermal power plant analysis.

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