

Energy And Exergy Analysis Of A Boiler With Different Fuels Like Indian Coal, Imported Coal And L.S.H.S. Oil Author - ANKIT PATEL

Energy sector is one of the important areas in the economic development of any country. Meeting the growing energy demands at acceptable costs in various sectors like industries, commercial, transport, etc., is the challenge to the energy planner.

The present work is an account of Energy and Exergy analysis of a Boiler in the captive power plant of "Nilkanth concast pvt ltd Anjar." The captive power plant of nilkanth concast pvt ltd, Anjar consists of 50 MW capacities Turbine Generator set (2 Unit). The capacity of the each Turbine Generator set is 25 MW. The capacity of the each Boiler for the steam generation 180 T/hr. coal, NG, and Oil fired boiler supplied by B.H.F.L. (3 Unit) and NG and Oil fired boiler supplied by Thermax babcock wilcox (1 Unit).

Some basic Concept regarding the Energy and Exergy are presented in the here. The theoretical analysis for simple process, such as those for a simple boiler is presented. The general overview of the Boiler Plant is discussed. The quantitative analysis of the plant and its equipment is carried out in. First the 1st law analysis for the system has been carried out. The analysis has been presented for the boiler.

After completing the whole 1st law analysis of the Boiler plant, the 2nd law analysis has been presented. The results obtained by 1st and 2nd law analysis are compared in this section. Some assumption made during calculations is also presented here along with the explanation for such assumptions. Finally concludes the work and the suggestions for future work.

Suitable computer programs are developed for both energy and exergy analysis of a Boiler plant. The analysis shows that the 1st law efficiency of Boiler Plant with different fuels like Indian coal, imported coal, (60% Imp + 40% Ind) coal and L.S.H.S oil are 76.54%, 83.03%, 80.60%, and 88.20% respectively and as well as exergetic (rational) efficiency of the Boiler Plant are 37%, 37.7%, 37.8% and 40.1% respectively.

METHODOLOGY OF FIRST LAW ANALYSIS:

The first law of thermodynamics states that a system executes a cyclic process, the net work is proportional to the net heat, mathematically.

$$\int dw = \int dq \quad \text{----- (1)}$$

Heat and work are different forms of same entity called energy which is conserved, energy which enters the system as heat may leave the system as work, or energy which enters the system as work may leave the system as heat. For non – cyclic process, the increase of energy of system, during the change of state is numerically equal.

$$Q - W = \Delta E \quad \text{----- (2)}$$

Thus in general first law gives the following two distinct assertions.

1. A system can interact with its surrounding in only two ways namely heat and work.

2. There is property called energy whose change gives net effect of these interactions.

In thermodynamics, a heat engine is defined as a continuously operating system at the boundary of which there is heat and work interaction. It is important to note that for conservation of energy it is necessary to pursue two objectives namely: reducing the demand of energy and to supply this demand at the maximum possible efficiency. The second objective is within the field of engineering community.

The concept of first law efficiency for heat engines or in general for thermodynamic cycle representing the fractional part of the heat supplied to a cycle, which is converted into work.

$$\eta_1 = W / Q_H \quad \text{----- (3)}$$

Therefore, first law efficiency is the ratio of quantitative value of desired output to the quantitative value of inputs used to produce that result. The efficiencies of different energy system involving different types of energy inputs and output cannot be compared directly. Identification of particular energy quantities as output and input give rise to different definitions for efficiency. Such definitions some times (as in case of electricity driven pumps and refrigerators) give rise to efficiency greater than one. This in its turn appearing anomalous.

The first law of thermodynamics has several short coming as given below:

1. Its maximum value may be greater than, equal to or less than unity. (Depending upon device and on the temperature).
2. It cannot be readily generalized to complex system in which the output is combination of heat and

work. (As in total energy system). This is because in the eyes of first law work and heat are equivalent quantitatively and qualitatively.

3. It completely ignores the second law implications, which play the central role in governing energy resource utilization and conservations.

3.5 EXERGETIC EFFICIENCY:

For a control volume at steady state the exergy equation can be written as follows,
Exergy = Exergy out in product + Exergy loss + Exergy destruction

The exergetic efficiency is a measure of performance in terms of optimal performance permitted by both first and second law of thermodynamics and is devoid of the drawbacks inherent in the definition of first law efficiency. For a device whose output is either work or heat transfer, it is defined as ratio of energy transfer achieved by device or system to the maximum possible heat or work usefully transferable by any device or system to the maximum possible heat or work usefully transferable by any device or system using the same energy input as the given system. While numerator is same for both first and second law efficiencies, the denominator in latter case brings both laws of thermodynamics directly into the definition of efficiency. First law focuses attention on reading losses, to improve efficiency. The second law efficiency point out that both 'losses' and 'internal irreversibility' need to be examined to improve performance.

From exergy balance, exergetic efficiency η_{EX} [11] is defined as, Exergy out in product

$$\eta_{EX} = \frac{\text{Exergy out in product}}{\text{Exergy in}} \quad \text{----- (4)}$$

$$\eta_{EX} = 1 - \left[\frac{\text{Loss + destruction}}{\text{Exergy in}} \right] \quad \text{----- (5)}$$

Input

Percentage loss of exergy in the components is defined as follows,

$$\emptyset_{EX} = \frac{[\text{Loss} + \text{destruction}]}{\text{Input}} * 100 \quad (6)$$

Input

Thus one can find out the components in which the losses are considerable, so that one can suggest the ways of reducing the losses and thus increase the exergetic efficiency.

ENERGY ANALYSIS:

Basically Boiler efficiency can be tested by the following methods:

The Direct Method: Where the energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel.

The Indirect Method: Where the efficiency is the difference between the losses and the energy input

The Direct Method Testing

$$\text{Boiler Efficiency} = \frac{\text{Heat Output}}{\text{Heat Input}} \times 100$$

$$\text{Efficiency} = \frac{\text{Heat addition to Steam} \times 100}{\text{Gross Heat in Fuel}}$$

$$\text{Boiler Efficiency} = \frac{\text{Steam flow rate} \times (\text{steam enthalpy} - \text{feed water enthalpy})}{\text{Fuel firing rate} \times \text{Gross calorific value}} \times 100$$

Parameters to be monitored for the

calculation of boiler efficiency by direct method are:

Quantity of steam generated per hour (Q) in kg/hr.

Quantity of fuel used per hour (q) in kg/hr.

The working pressure (in bar) and superheat temperature (K), if any

The temperature of feed water (K)

Type of fuel & gross calorific value of the

$$\text{Boiler Efficiency } (\eta) = \frac{Q \times (h_g - h_f)}{q \times \text{GCV}} \times 100$$

fuel (GCV) in kJ/kg of fuel

The Indirect Method Testing

The following losses are applicable to liquid, gas and solid fired boiler

L1 - Loss due to dry flue gas (sensible heat)

L2 - Loss due to hydrogen in fuel (H₂)

L3 - Loss due to moisture in fuel (H₂O)

L4 - Loss due to moisture in air (H₂O)

L5 - Loss due to carbon monoxide (CO)

L6 - Loss due to surface radiation, convection and other unaccounted*.

*Losses which are insignificant and are difficult to measure.

The following losses are applicable to solid fuel fired boiler in addition to above

L7 - Unburnt losses in fly ash (Carbon)

L8 - Unburnt losses in bottom ash (Carbon)

Boiler Efficiency by indirect method = 100
- (L1 + L2 + L3 + L4 + L5 + L6 + L7 + L8)

Conversion formula for proximate analysis to ultimate analysis

We know that minimum mass of

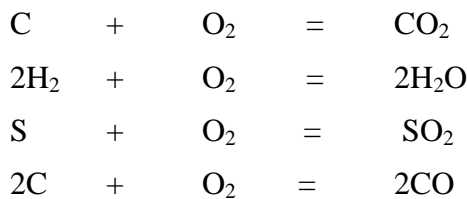
%C	=	0.97C + 0.7 (VM + 0.1A) - M(0.6 - 0.01M)
%H ₂	=	0.036C + 0.086 (VM - 0.1xA) - 0.0035M ² (1 - 0.02M)
%N ₂	=	2.10 - 0.020 VM
C	=	% of fixed carbon
A	=	% of ash
VM	=	% of volatile matter
M	=	% of moisture

air required for complete combustion of 1 kg of fuel

$$= (100 / 23) * \{((8 / 3) * C + 8 * H_2 + S) - O_2\} \text{ kg}$$

4.96 kg/kg of coal

The products of combustion are represented by the following chemical equations:



Percentage composition of dry flue gases by volume

$$CO_2 = (1.46 / 7.76962) * 100 = 18.86 \%$$

$$SO_2 = (0.01 / 7.76962) * 100 = 0.126 \%$$

$$O_2 = (0.57 / 7.76962) * 100 = 07.31 \%$$

$$N_2 = (5.72 / 7.76962) * 100 = 73.70 \%$$

% Heat loss in dry flue gas (L₁) =

$$\frac{m \times C_p \times (T_f - T_a)}{\text{GCV of fuel}} \times 100$$

$$= 5.91 \%$$

% Heat loss due to formation Of water from H₂ in fuel (L₂) =

$$\frac{9 \times H_2 \times \{584 + C_p (T_f - T_a)\}}{\text{GCV of fuel}}$$

$$L_2 = 3.66 \%$$

% Heat loss due to moisture in fuel (L₃)

$$= \frac{M \times \{584 + C_p (T_f - T_a)\}}{\text{GCV of fuel}}$$

$$L_3 = 2.39 \%$$

% Heat loss due to moisture in air (L₄)

$$= \frac{\text{AAS} \times \text{humidity} \times C_p \times (T_f - T_a) \times 100}{\text{GCV of fuel}}$$

$$L_4 = 0.17$$

% Heat loss due to partial conversion of C to CO (L₅) =

$$\frac{\%CO \times C}{\%CO + (\%CO_2)_a} \times \frac{574400}{\text{GCV of fuel}}$$

$$L_5 = 2.58 \%$$

Heat loss due to radiation & convection (L₆) =

$$0.548 \times [(T_s/55.55)^4 - (T_a/55.55)^4] + 1.957 \times (T_s - T_a)^{1.25} \times \text{sq.rt of } [(196.85 \times V_m + 68.9) / 68.9]$$

$$L_6 = 0.46 \%$$

% Heat loss due to Unburnt in fly ash =

$$\begin{aligned} \text{Amount of fly ash in 1 kg of coal} &= 0.3 * 0.4373 \\ \text{Heat loss in fly ash} &= 0.13119 * 1894.16 \\ \% \text{ heat loss in fly ash} &= \frac{248.49 * 100}{13995.47} \\ L_7 &= 1.77 \% \end{aligned}$$

% Heat loss due to Unburnt in bottom ash =

$$\begin{aligned} \text{Amount of bottom ash in 1 kg of coal} &= 0.7 * 0.4373 \\ \text{Heat loss in bottom ash} &= 0.30611 * 2982.52 \\ \% \text{ heat loss in bottom ash} &= \frac{912.98 * 100}{13995.47} \\ L_8 &= 6.52 \end{aligned}$$

Boiler efficiency by indirect method =

$$100 - (L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + L_8) \\ = 76.54 \%$$

and heat being only exchanged with the environment at T_0 ”.

The basic Exergy equation for one kg substance in flowing open systems, disregarding kinetic and potential exergy terms is as follows:

$$Ex = (H - H_0) - T_0 (S - S_0)$$

Often a subdivision into physical, chemical and mixing exergy is made. In calculating the exergy flow, the exergy terms are multiplied by the flow:

$$EX_{Total} = m (EX_{Chem} + EX_{Phys} + \Delta EX_{Mix})$$

Fuel	L1	L2	L3	L4	L5	L6	L7	L8	Total	Efficiency
Indian Coal	5.9	3.6	2.3	0.17	2.58	0.46	1.77	6.52	23.46	76.54
Imported Coal	5.5	3.7	1.5	0.16	2.42	0.33	0.68	2.5	16.97	83.03
(60% Imp + 40% Ind) coal	5.8	3.9	1.8	0.17	2.54	0.37	1.01	3.72	19.4	80.60
LSHS Oil	5.2	5.9	0.02	0.24	-	0.30	-	-	11.80	88.20

Energetic Efficiency of Various fuel used in Boiler

Fuel	L1	L2	L3	L4	L5	L6	L7	L8	Total	Heat Input	Available Heat	%
Indian Coal	827.1	512.2	334.4	23.7	361.0	64.3	247.6	912.4	3283.06	13995.47	10712.41	76.54
Imported Coal	1062.6	719.6	289.3	30.13	460.8	62.8	129.5	476.07	3231.75	19043.99	15812.24	83.03
(60% Imp + 40% Ind) coal	995.84	670.7	306.5	28.88	432.4	62.8	171.9	633.04	3302.75	17024.62	13721.83	80.60
LSHS Oil	2342.9	2640.1	10.5	109.25	-	136	-	-	5239.19	44371.6	39132.23	88.20

Heat Losses in Various Fuels used in Boiler (kJ/kg of fuel)

EXERGY ANALYSIS:

“ The exergy of a material stream is the maximum obtainable amount of shaft work (or electrical energy) when this stream is brought from actual conditions (T, P) to thermo mechanical equilibrium at ambient conditions (T_0, P_0) by reversible processes

Hence from 'Kotas' for dry organic substance contained in solid fuels consisting of C, H, O, and N, with a mass ratio of oxygen to carbon less than 0.667, the following expression was obtained in terms of mass ratios.

$$\Phi_{\text{dry}} = 1.0437 + 0.1882 \times (h/c) + 0.0610 \times (o/c) + 0.0404 \times (n/c)$$

Where c, h, o, and n are the mass fractions of C, H, O, and N respectively. Within the restriction regarding the upper limit of o/c, is applicable to a wide range of industrial solid fuels but not to wood. The accuracy of the expression is estimated to be better than $\pm 1\%$.

For the fossil fuels with the mass ratio $2.67 > o/c > 0.667$, which in particular, includes wood.

$$\Phi_{\text{dry}} = \frac{1.0438 + 0.1882 \times (h/c) - 0.2509[1 + 0.7256 \times (h/c) - 0.0383 \times (n/c)]}{1 - 0.3035 \times (o/c)}$$

For liquid fuels the effect of sulphur was included in the correlation giving the expression:

$$\Phi = 1.0401 + 0.1728 \times (h/c) + 0.0432 \times (o/c) + 0.2169 \times (s/c) \times [1 - 2.0628 \times (h/c)]$$

Hence the Φ is the ratio of chemical exergy to the calorific value of a fuel. The significance of Φ is that, it is assumed that Φ is same for the fuel and a pure chemical substance having the same ratios of constituent chemicals as that of fuel.

Now Chemical Exergy is given as

$$\epsilon^0 = [\text{Calorific value (kJ/kg)} + 2442 \times (\text{Moisture})] \times \Phi + 9417 \times \text{Sulphur}$$

EXERGY ANALYSIS OF THE BOILER:

Sub Region I Combustion Chamber

Sub Region II Heat Transfer to Water

Sub Region III Flue gas mixing with atmosphere

Analysis of Sub Region I:

Here, assuming that the combustion process is adiabatic.

Since air enters this sub region at atmospheric conditions so we get,

$$T_1 = T_0$$

$$P_1 = P_0$$

Employing energy balance between Section 1 and Section 2 so,

$$m_{\text{Fuel}} \times \text{GCV} = (\theta_2 - \theta_1) \sum n \text{Cp}^h$$

Where

n = No of moles

Cp^h = Molar specific heat of gas.

In this equation θ_2 is unknown and hence Cp^h is also unknown (it is a function of temperature). Now value of θ_2 finding out by iteration method and for Cp^h use table in the Annexure IV.

Exergy balance in the sub region I gives

$$I_1 = \text{EX}_1 - \text{EX}_2$$

$$\text{Where, } \text{EX}_1 = \text{EX}_{\text{Fuel}} + \text{EX}_{\text{Air}}$$

$$\text{EX}_1 = \text{EX}_{\text{Fuel}}$$

$$\text{Since, } \text{EX}_{\text{Air}} = 0$$

$$\text{EX}_2 = n_{p2} \times \epsilon_{p2}^0 + \sum n \epsilon_p^h$$

$$\text{Now, } \epsilon_{p2}^0 = \sum X_K \epsilon_K^0 + R T_0 \sum X_K \ln X_K$$

$$\sum n \epsilon_p^h = (\theta_2 - \theta_0) \sum n \text{Cp}^\epsilon$$

$$\text{And, } Ex_1 = m_{\text{Fuel}} \times \epsilon_{\text{Fuel}}^0$$

The value of ϵ_k^0 is taken from the Annexure IV. ϵ_{p2}^0 is the component of exergy of component gases. The physical component of exergy of the combustion gases is calculated by using data extracted from Annexure IV at temperature θ_2 .

Hence irreversibility of Sub Region is

$$I_1 = Ex_1 - Ex_2$$

So, the 2nd law efficiency of region I is

$$\eta_{2}^{\text{nd law}} = (Ex_2 / Ex_1) \times 100\%$$

Analysis of Sub Region II:

To find the heat lost Q_L from the boiler, energy balance of the sub region II.

$$H_2 + h_{\text{FW}} m_{\text{FW}} = H_3 + m_s h_s + Q_L$$

Where, H_2 = Enthalpy of incoming combustion product

H_3 = Enthalpy of flue gas

Q_L = Heat Lost

h_{FW} = Specific enthalpy of feed water

m_{FW} = Mass of feed water

h_s = Specific enthalpy of super heating steam

m_s = Mass of super heating steam

$$\text{Now, } H_2 = (\theta_2 - \theta_0) \Sigma n C_p^h$$

$$\text{And, } H_3 = (\theta_3 - \theta_0) \Sigma n C_p^h$$

Now Exergy Balance,

$$Ex_2 + Ex_{\text{FW}} = Ex_3 + Ex_S + I_2$$

Irreversibility,

$$I_2 = (Ex_2 - Ex_3) - (Ex_S - Ex_{\text{FW}})$$

Where, $Ex_3 = Ex_3^0 + Ex_{\text{ph3}}$

$Ex_3^0 = Ex_2^0$ = Chemical Exergy of gases.

Ex_{ph3} = Physical Exergy at Temperature θ_3

$$= (\theta_3 - \theta_0) \Sigma n C_p^e$$

Hence the efficiency of the sub region II

$$\eta_{2}^{\text{nd law}} = [(Ex_S - Ex_{\text{FW}}) / Ex_2] \times 100\%$$

Analysis of Sub Region III:

In this sub region the flue gases mix with atmosphere. So the exergy of the flue gases coming out from the boiler is entirely lost as irreversibility.

So, Irreversibility $I_3 = Ex_3$

Hence the rational efficiency of the boiler is

$$\Psi = [(Ex_S - Ex_{\text{FW}}) / Ex_1] \times 100\%$$

RESULT AND DISCUSSION ON EXERGY ANALYSIS:

The study of this analysis indicates that the Exergetic efficiency of sub region I, II, III (rational efficiency) and combustion efficiency of the Indian coal fired Boiler are of the order of 73.43%, 55.70%, 37.00% and 85.24% respectively.

Exergetic Efficiency of Various fuel used in Boiler

Fuel	Sub Region			Combustion Efficiency η_{comb}
	I	II	III (Ratio nal efficiency)	
Indian Coal	73.43	55.70	37.00	85.24
Imported Coal	73.70	55.78	37.70	84.90
(60% Imp + 40% Ind) coal	73.55	55.73	37.80	84.40
LSHS Oil	76.41	62.13	40.10	90.20

CONCLUSION:

From the energy and the exergy analysis of the Boiler Plant (Indian coal as a fuel), it is seen that the energy analysis attributes all the inefficiencies to losses as 23.46%. The first law efficiency of the Boiler plant is 76.54%, while the Exergetic efficiency of the plant is 37.00%.

One can see that there is a huge difference between the first law efficiency and second law efficiency of the Boiler plant such as 76.54% and 37.00% respectively. This is due to large amount of energy degradation. This degradation of energy increases the entropy and hence a decrease in the exergy or second law efficiency.

From the exergy analysis of the Boiler plant it is also seen that major inefficiencies are due to the heat transfer and combustion process, the stack losses are comparatively very less. An energy analysis shows that combustion process is 100% efficient and heat transfer is also highly efficient, while stack gases carry away the majority of the lost energy. Thus first law efficiency is the poor approximation of true efficiency and misleads as far as the performance of the Boiler plant is concerned.

It has been seen that the maximum loss of exergy is while converting the chemical exergy such as 150329.66 kJ/kg of fuel to heat. This is due to the high production of entropy during the process of burning of fuel. Maximum of exergy is lost during this process of conversion. By supplying air – fuel at high temperature, the production of entropy can be reduced and hence higher combustion efficiency may be obtained.

Second law analysis indicates the destruction of exergy of various components of the Boiler plant. Therefore to increase second law efficiency (Exergetic efficiency is 37.00%) of the plant attempt should be made to reduce the destruction of exergy as far as possible.

To increase boiler efficiency by 1% to reduce temperature of flue gas at 22 °C so that preheat combustion of air with waste heat. Improve oxygen trim control (e.g. limit excess air to less than 10% on clean fuels). 5% reduction in excess air increases boiler efficiency by 1% or 1% reduction of residual oxygen in stack gas increases boiler efficiency by 1%. And also 6 °C raise in feed water temperature by economizer recovery corresponds to a 1% saving in fuel consumption, in boiler.

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