ISSN 2348-1218 (print)
International Journal of Interdisciplinary Research and Innovations ISSN 2348-1226 (online)
Vol. 6, Issue 3, pp: (672-683), Month: July - September 2018, Available at: www.researchpublish.com

Energy and Exergy Analysis of Boiler and Extraction cum Condensing Steam Turbine in Sugar Cogeneration Plant

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Abstract: **The demand for energy is increasing day by day. The energy for the world depends heavily on fossil fuels for electricity generation. It is also expected to continue the dependence on fossil fuels for next few decades. So it is important to note that this plants must reduce their environmental impact by operating fossil fuels more effectively. Energy analysis based on first law of thermodynamics cannot be applied as it cannot justify the real useful energy loss because it does not differentiate between quality and quantity of energy within the system. Whereas exergy analysis will characterize the work potential of a system based on the second law of thermodynamics and the maximum work that can be obtained from the system when its state is brought to the reference or dead state. The paper presents the results of energy and exergy analysis of boiler and extraction cum condensing steam turbine of 18.9 MW cogeneration plant. It is seen that maximum exergy destruction occurs in boiler particularly during combustion process. The energy analysis of boiler and steam turbine is 66.08 % and 78.26% while exergy analysis of boiler and steam turbine is 42.55% and 74.74 % respectively. The exergy destruction in boiler is 31.472 MW.**

Keywords: **Energy, Efficiency, Exergy, Exergy destruction, power plant, cogeneration.**

I. INTRODUCTION

The first law of thermodynamics is often referred to as the law of conservation of energy. It states that energy can neither be created nor destroyed but may be converted from one form into another. Energy conversion processes are governed by the laws of conservation of mass and energy. The first law allows one to construct an energy balance around the given process. It does not provide any useful information with regards to how energy is transferred. The second law of thermodynamics accounts for directionality and explains the irreversibility of any process. Entropy is generated and exergy is destroyed by irreversibilities within a thermal system. Exergy is lost, when the exergy associated with a material or energy is rejected to the surroundings.

In this paper energy and exergy analysis of boiler and turbine is carried out. The objective is to calculate the real thermodynamic efficiencies of components and to understand the effects of it. Sources of inefficiencies are related to exergy destruction and exergy loss. Either an exergy balance or an entropy balance together with the relationship $E=T_oS$ can be used to calculate the exergy destruction in a component. The main contributors to exergy destruction are irreversibilities associated with chemical reaction, heat transfer, mixing and friction.

II. LITERATURE SURVEY

Aljundi [1] in his paper presented the energy and exergy analysis of Al-hussein power plant in Jordan. The primary objectives of this paper is to analyse the system components separately and to identify and quantify the sites having largest energy and exergy losses. In addition, the effect of varying the reference environment state on this analysis will also be presented. Energy losses mainly occurred in the condenser where 134MW is lost to the environment while only 13MW was lost from the boiler system. The percentage ratio of the exergy destruction was found to be maximum in the boiler system (77%) followed by the turbine (13%) and then forced draft fan condenser (9%). In addition the calculated thermal efficiency based on the lower heating value of fuel was 26% while the exergy efficiency of the power cycle was 25%. For a moderate change in the reference environment state temperature, no drastic change was noticed in the performance of major components.

Rosen [11] presented energy and exergy based comparisons of coal fired and nuclear electrical generating stations. Overall energy and exergy efficiencies respectively are 37% and 36% for the coal fired process and 30% and 31% for the nuclear process. The losses in both plants exhibit many common characteristics. Energy losses associated with emissions account for all of the energy losses, while emission related exergy losses account for approximately 10% of the exergy losses. The remaing exergy losses are associated with internal consumptions.

Kaushik [4] presented a review on energy and exergy analysis of thermal power plant. A comparison between thermal power plant stimulated by coal and gas was made. For coal based thermal power plant, obtained results show that the highest energy loss is located in the boiler. While for gas fired combined cycle thermal power plant the maximum losses are located in the combustion chamber.

Ray [3] developed an exergy analysis for proper operating and maintenance decisions in a 500 MW steam power plant. The study is conducted considering design and off-design conditions for various values of superheat and reheats sprays. Obtain results constitute guide procedures for exergy, economy and maintenance scheduling similar power plants.

Erdem[14] A comparison between nine coal-fired power plants in Turkey is conducted for each plant. A calculation model is proposed and the mass, energy and exergy balances are established. That permits to determine the energy and exergy efficiency as well the exergy destruction rate of each component. A comparison is then accomplished between the considered power plants. The obtained results may constitute helpful tools for further investigations in the field of energetic and exergetic industrial power plant analysis.

III. METHODOLOGY

Second law of thermodynamics defines the maximum work potential of a system or heat interaction, the state of the environment being used as a datum state. Open flow system consists of three types of energy transfer across the control surface namely work transfer, heat transfer and energy associated with mass transfer. The work transfer is equivalent to maximum work which can be obtained from that form of energy. The availability of heat transfer from the control surface at temperature T is determined from maximum rate of conversion of thermal energy to work W_{max}.

the maximum work is given by

$$W_{max} = Q(1- T_a/T)$$

The energy analysis is based on the first law of thermodynamics which is related to the conservation of energy. second law analysis is a method that uses the conservation of mass and conservation of energy principles together with the entropy for analysis, design and improvement of energy system .

The first law of thermodynamics or energy balance for steady flow process of an open system is given by

$$Q-W +m(E_1 -E_2) = 0$$

where E_1 and E_2 are energy associated with mass entering and leaving

Q = heat transfer to system from source at temp. T

W = net work developed by system

The second law of thermodynamics for steady flow process of an open system is given by

$$E_{x1} - E_{x2} + m(\Psi_1 -\Psi_2) -IR = 0$$

where

Ψ_1 and Ψ_2 are available exergy associated with mass inflow and outflow respectively

E_{x1} and E_{x2} are available energy associated with heat transfer and work transfer

IR = irreversibility of process

The energy or first law efficiency of a system is defined as the ratio of energy output to the energy input of system.

$$\eta_I = \text{desired output energy/Input energy supplied}$$

$\eta_I = (E_{in} - E_{out})/E_{in}$

The second law efficiency is defined as

η_{II} = Desired output /max. possible output

$\eta_{II} = \Psi_{power}/ (\Psi_{in} - \Psi_{out})$

Exergy destruction $\Psi_{des} = \Psi_{in} - \Psi_{out} - \Psi_{power}$

Description of the cogeneration plant

S.S.K. cogeneration plant is located in basmath nagar, Dist Hingoli,Maharashtra. The schematic of the cogeneration plant and mass balance of the system is shown in fig 1. The diagram shows different equipments used in cogeneration plants along with their operating parameters. It is a 2500 tcd sugar factory, satisfying its process steam demand from condensing steam turbine.

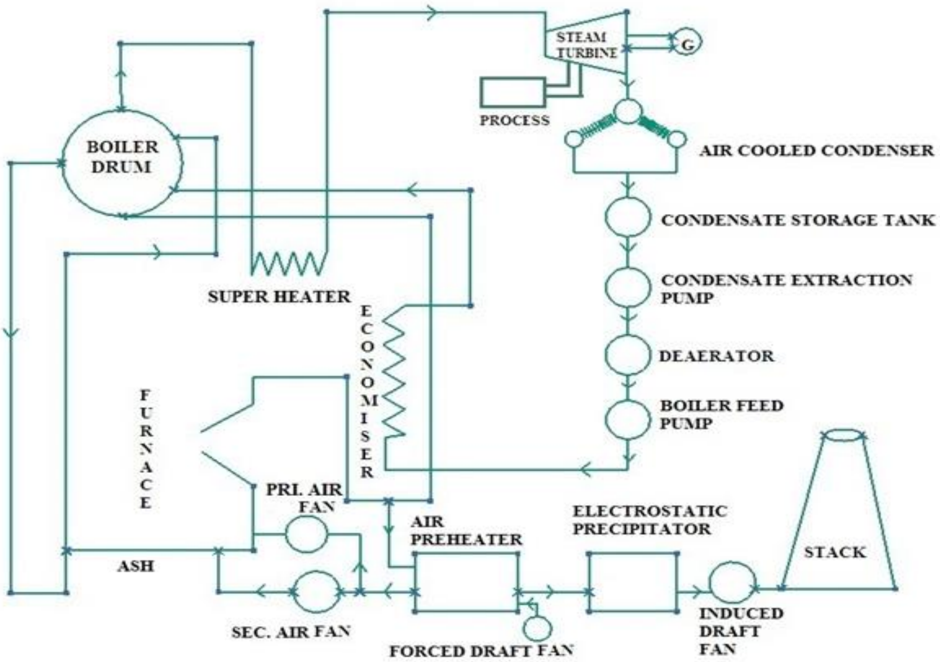

Fig.1: S.S.K Cogeneration plant

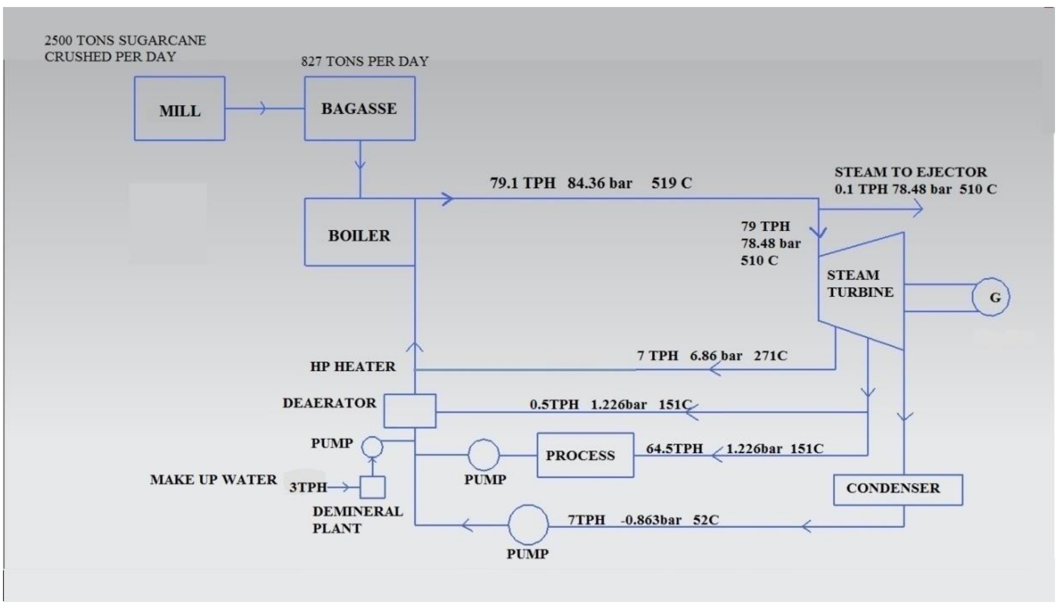

Fig. 2: S.S.K. Cogeneration plant with operating parameters

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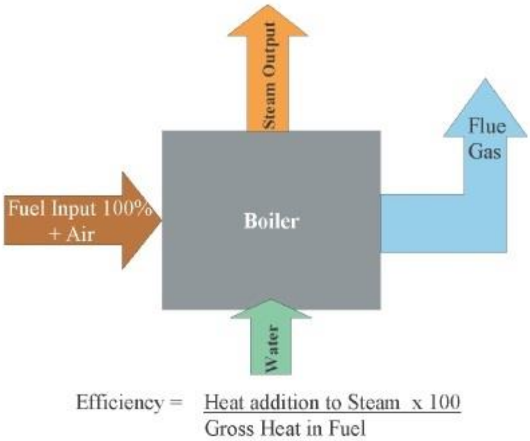
IV. ENERGY ANALYSIS OF BOILER

1. Direct Method/Input output method

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



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

1. Direct Method/Input output method

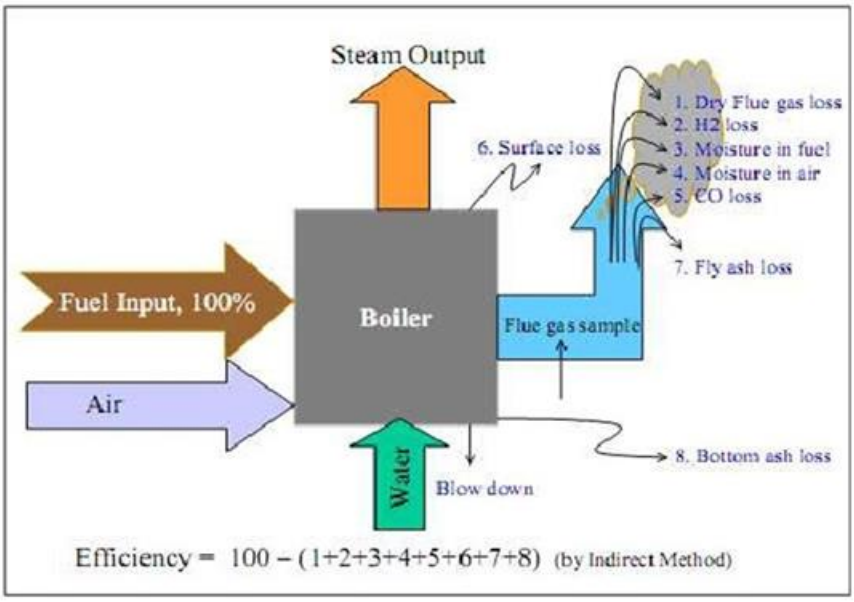
Efficiency of boiler

η_b = (Heat output/Heat input) x 100

= Steam flow rate x (enthalpy of steam - enthalpy of feed water)/ (Fuel firing rate x GCV)

2. Indirect method or Heat loss method:

Losses in Boiler



In this method efficiency of boiler can be calculated by considering the heat losses in boiler. In direct method these heat losses were not considered so indirect method has the advantages over direct method.

Losses in boiler

1. Loss of heat due to dry flue gases (L1)

2. Loss of heat due to hydrogen in fuel (L2)

3. Loss of heat due to moisture present in fuel (L3)

4. Loss of heat due to moisture present in air (L4)

5. Loss of heat due incomplete combustion of fuel (L5)

6. Loss of heat due to convection and radiation (L6)

7. Loss of heat due to unburnt carbon in flyash (L7)

8. Loss of heat due to unburnt carbon in bottom ash (L8)

Total losses = L1+L2+L3+L4+L5+L6+L7+L8

Boiler efficiency = 100 - (L1+L2+L3+L4+L5+L6+L7+L8)

Table 1. Ultimate analysis of bagase

Constituent	% wt.
Carbon (c)	22.98
Hydrogen (H_2)	3.96
Oxygen (O_2)	21.81
Moisture	49.83
Ash	1.32
Pol	2.16

GCV of bagasse

GCV =4600 x (1 - moisture in bagase)-1200 x bagasse pol

= 2282 Kcal/kg

Table 2. Operating parameters for boiler

Steam generation	Kg/s	21.972
Steam pressure	bar	84.366
Steam temperature	°C	519
Ambient temp	°C	33
Humidity in ambient air	Kg/Kg of air	0.0204
GCV of bagase	Kcal/Kg	2282
GCV of bottom ash	Kcal/Kg	600
GCV of fly ash	Kcal/kg	252.5
Furnace temp	°C	750
Furnace pressure	mmwc	-1.12
Drum level	%	43
Feed water temp.	°C	114
O_2 in Flue gas	%	4
CO_2 in flue gas	%	8.45

Theoretical air required

$$= [11.6 \text{ x } c + \{34.8\text{x}(H_2 - \frac{O_2}{8})\} + 4.35 \, s]/100$$

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$$= \frac{11.6\ x\ 22.98 + \{34.8\ x\ (3.96 - (\frac{21.81}{8})\}}{100}$$

= 3.095 kg/kg of fuel

Excess air supplied

(EA) = O_2 %/(21 - O_2 %) x 100

= 23.52%

Actual mass of air supplied

AAS = $(1 + \frac{EA}{100})$ x theoretical air require

= (1 + 23.52/100) x 3.095 =3.823 kg/kg of fuel

Actual mass of dry flue gas (m_{fg})

(C x 44/12) + N_2/100 + (AAS x 77/100) + (AAS - theoretical air) x 23/100

= 3.955 kg/kg of fuel

1. % of heat loss due to dry flue gases (L1)

$$L1 = \frac{m_{fg}\ c_{pg}(T_{fg} - T_a)}{GCV\ of\ fuel}\ x\ 100$$

= 3.955 x 0.24 x (134 - 33) x 100/2282

= 4.201%

2. % of heat loss due to evaporation of water formed due to hydrogen in fuel (L2)

$$L2 = \frac{9\ x\ H_2\ x\{584 + C_p(T_f - T_a)\}x\ 100}{GCV\ of\ fuel}$$

$$= \frac{9\ x\ 0.0396\ x\ \{584 + 0.45(134 - 33)\}x\ 100}{2282}$$

= 9.83 %

3. % of heat loss due to moisture present in fuel (L3)

L3 = [M x { 584 + $C_p(T_{f\,g} - T_a)$}] x 100 / GCV of fuel

= [0.4983 x { 584 + 0.45(134 - 33)}] x 100 / 2282

= 13.744%

4. % of heat loss due to moisture present in air (L4)

L4 = {AAS xsp. Humidity x C_p $(T_f - T_a)$ x 100}/GCV of fuel

= {3.823x 0.024 x 0.45(134 - 33) x 100}/2282

= 0.182 %

DBT = 40°C WBT = 30°C Relative humidity = 50% specific humidity = 0.024

5. % of heat loss due to incomplete combustion (L5)

L5 = (% CO x C) /(% CO + % CO_2) x (5744/GCV of fuel)} x 100

= 5.399 %

6. % of heat loss due to convection and radiation.(L6)

L6 = = { h x A x $(T_s - T_a)$ x 100 }/(F_{hr} x GCV }

h = 4.87 x $10^{(-8)}$ x ε x{$(T_s + 273)^4 - (T_a + 273)^4$}/($T_s - T_a$) + 1.683 x ($T_s - T_a)^{0.25}$ x (2.857 x v + 1)

L6 = 0.2324%

ε = 0.6 v = 3.5 m/s

7. % of heat loss due to unburnt carbon in flyash (L7)

Ratio of fly ash to bottom ash is 10 : 90

also ash = 1.32%

L7 = {Total ash collected per kg of fuel burnt x GCV of fly ash} x 100/GCV of fuel

= (0.1 x 0.0132 x 252.5 x100) /2282

= 0.0144 %

8. % of heat loss due to unburnt carbon in bottom ash (L8)

L8 = {Total ash collected per kg of fuel burnt x GCV of bottom ash} x 100/GCV of fuel

= (0.9 x 0.0132x600x100)/2282

= 0.312 %

Efficiency of boiler

η_b = 100 - (L1+L2+L3+L4+L5+L6+L7+L8)

= 100 - (4.201+9.83+13.744+0.182+5.399+0.232+0.0144+0.312)

= 66.08 %

EXERGY ANALYSIS OF BOILER

1. Exergy of fuel (Ψ_f)

Ψ_f =34183.16(C) + 21.95(N) +11659.9 (H)- 13265.90 (O) - (298.15 x S_{ash} x m_{ash}) + 0.63(O) {7837.667(C) + 33888.889(H) - 4236.10(O)}

=34183.16(0.2298) + 21.95(0.001) +11659.19(0.0396) - 13265.90(0.2181) - (298.15 x 0.84 x0.0132) + 0.63(0.2181){7837.66 x 0.2298 + 33888.889 x 0.0396 -4236.10 x 0.2181}

= 54.788 MW

2. Exergy of feed water (Ψ_w)

$\Psi_w = C_{pw}(T_w - T_a) - T_a \ln(T_w/T_a)\}$

= 4.187{(114 -33) - 306 In(387/306)}

= 6.125 MW

3. Exergy of steam formed (Ψ_s)

$\Psi_s = (h_g - h_f) - T_a (S_g - S_a)$

= (3439.164- 485.804) - 306(6.748 - 1.462)

= 29.348 MW

4. Exergy of air supplied (Ψ_a)

$\Psi_a = C_{pa}(T_2 - T_a) - T_a \ln(T_2/T_a)$

= 1.0037(120 -33) -306 In(393/306)

= 0.041 MW

5. Exergy of flue gas (Ψ_{fg})

$\Psi_{fg} = C_{pg}(T_{fg} - T_a) - T_a \ln(T_{fg}/T_a)$

= 1.2 x(134 - 33) -306 In(409/306)

= 0.134 MW

Exergy destruction in boiler (Ψ_{des})

Ψ_{des} = Total exergy entering the boiler - Total exergy leaving the boiler

= $(\Psi_f + \Psi_w + \Psi_a) - (\Psi_s + \Psi_{fg})$

= 31.472 MW

Exergetic efficiency of boiler or IInd Law efficiency

$\eta_{II} = \{(\Psi_{fg} + \Psi_s) - (\Psi_w + \Psi_a)\} / \Psi_f$

= 42.55%

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Table 4. Operating parameters of steam turbine

Sr. No	component	symbol	unit	Value
1	Inlet steam flow	m_i	TPH	79
2	Inlet steam pressure	p_s	bar	78.48
3	Main steam temp.	T_s	°C	510
4	Enthalpy of main steam	h_i	KJ/kg	3423.725
5	Entropy of main steam	S_s	KJ/kgk	6.77
6	Extraction 1 flow	m_{ex1}	TPH	7
7	Extraction 1 temp.	T_{ext1}	°C	271
8	Extraction 1pressure	P_{ext1}	bar	6.867
9	Enthalpy of 1 ext steam	h_{ext1}	KJ/kg	2995.785
10	Entropy of 1 ext steam	S_{ext1}	KJ/kgk	7.188
11	Extraction 2 flow	m_{ext2}	kg/s	0.5
12	Extraction 2 temp.	T_{ext2}	°C	151
13	Extraction 2 pressure	P_{ext2}	bar	1.226
14	Enthalpy of 2 ext steam	h_{ext2}	KJ/kg	2770.0172
15	Entropy of 2 ext steam	S_{ext2}	KJ/kgk	7.5165
16	Extraction 3 flow	m_{ext3}	TPH	64.5
17	Extraction 3 pressure	P_{ext3}	bar	1.226
18	Extraction 3 temperature	T_{ext3}	°C	151
19	Enthalpy of 3 ext steam	h_{ext3}	KJ/kg	2770.0172
20	Entropy of 3 ext steam	S_{ext3}	KJ/kgk	7.5165
21	Exhaust steam flow	m_{exh}	TPH	7
22	Exhaust steam temp	T_{exh}	°C	52
23	Exhaust steam pressure	P_{exh}	bar	-0.863
24	Enthalpy of exhaust steam	h_{exh}	KJ/kg	2677.76
25	Entropy of exhaust steam	S_{exh}	KJ/kgk	7.405

Energy analysis of turbine

1. Energy input

$E_i = m_i \times h_i$

$= 21.944 \quad \times 3423.725$

$= 75130.2214$ KJ/s.

2. Energy output is sum of heat extracted and heat exhausted.

$E_o = (m_{ext1}h_{ext1}) + (m_{ext2}h_{ext2}) + (m_{ext3}h_{ext3}) + (m_{exh}h_{exh})$

$= (1.947 \times 2995.785) + (0.1388 \times 2770.0172) + (17.916 \times 2770.0172) + (1.944 \times 2677.76)$

$= 61053.930$ KJ/s.

3. Work done

$W.D. = E_i - E_o$

$= 75130.2214 - 61053.930$

$= 14076.2914$ KJ/s

4. Actual power developed by turbine shaft(P)

$P = \text{Generator power}/(\eta_{generator} \times \eta_{gearbox})$

$= 10639.841/(0.985 \times 0.9805)$

$= 11016.694$ KW

5. Energy efficiency (I[st] Law efficiency) of turbine:

$\eta_I = P/(E_i - E_o)$

$= 11016.694 / 14076.2914$

$= 78.26\%$

Exergy balance equation

$W_{max} = \Psi_{in} - \Psi_{out}$

1.Exergy Input

$\Psi_{in} = m_s (h_s - T_o S)$

$= 21.944 (3423.725 - 306 \times 6.77)$

$= 29536.2948$ KJ/s

2. Exergy output

$\Psi_{out} = m_{ext1}(h_{ext1} - T_o S_{ext1}) + m_{ext2}(h_{ext2} - T_o S_{ext2}) + m_{ext3}(h_{ext3} - T_o S_{ext3}) + m_{exh}(h_{exh} - T_o S_{exh})$

$=1.949(2995.785-306x7.188)+0.1388(2770.0172- 306x7.51652)+17.916(2700.0172-306x 7.5165)+1.944(2677.76 - 306 x 7.405)$

$= 10703.4048$ KJ/S

$W_{max} = \Psi_{in} - \Psi_{out}$

$= 29536.2948 - 10703.4048$

$= 18832.89$ KJ/S

$\Psi_{des} = W_{max} - W.D.$

$= 4.756$ MW

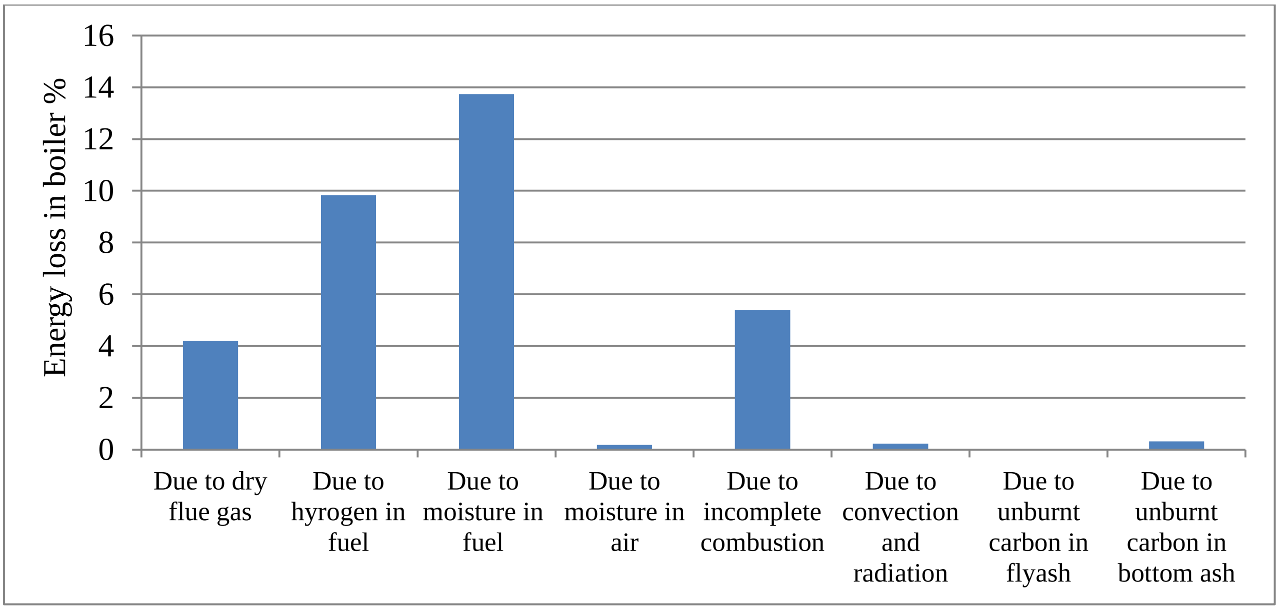
4. Exergy Efficiency (II[nd] law efficiency) of turbine

$\eta_{II} = WD / W_{max}$

$= 14076.2914 / 18832.89$

$= 74.74\%$

V. RESULTS



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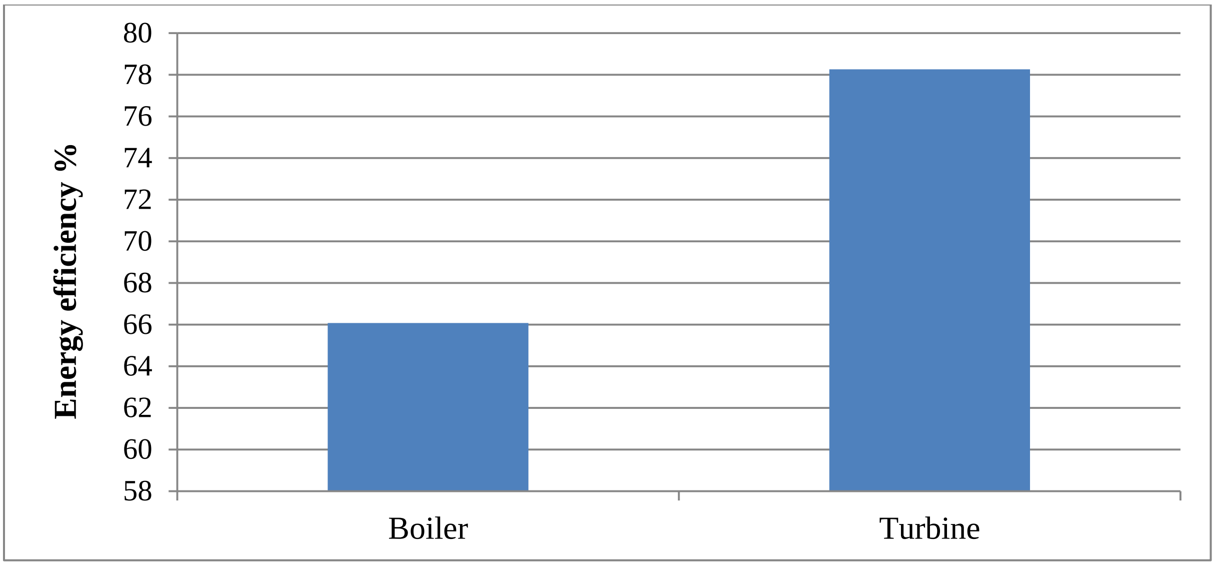

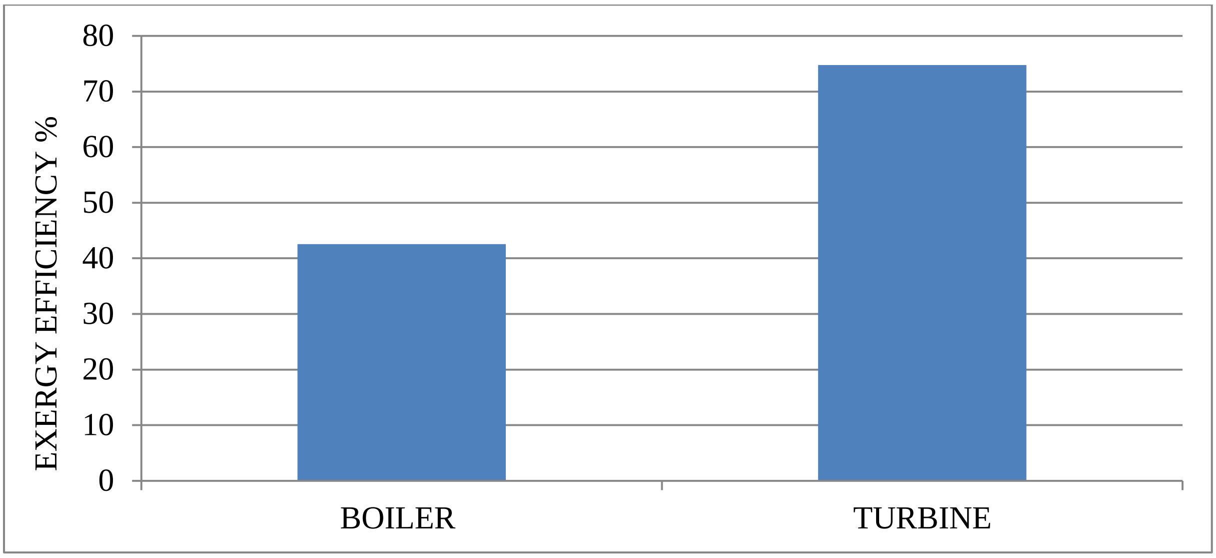

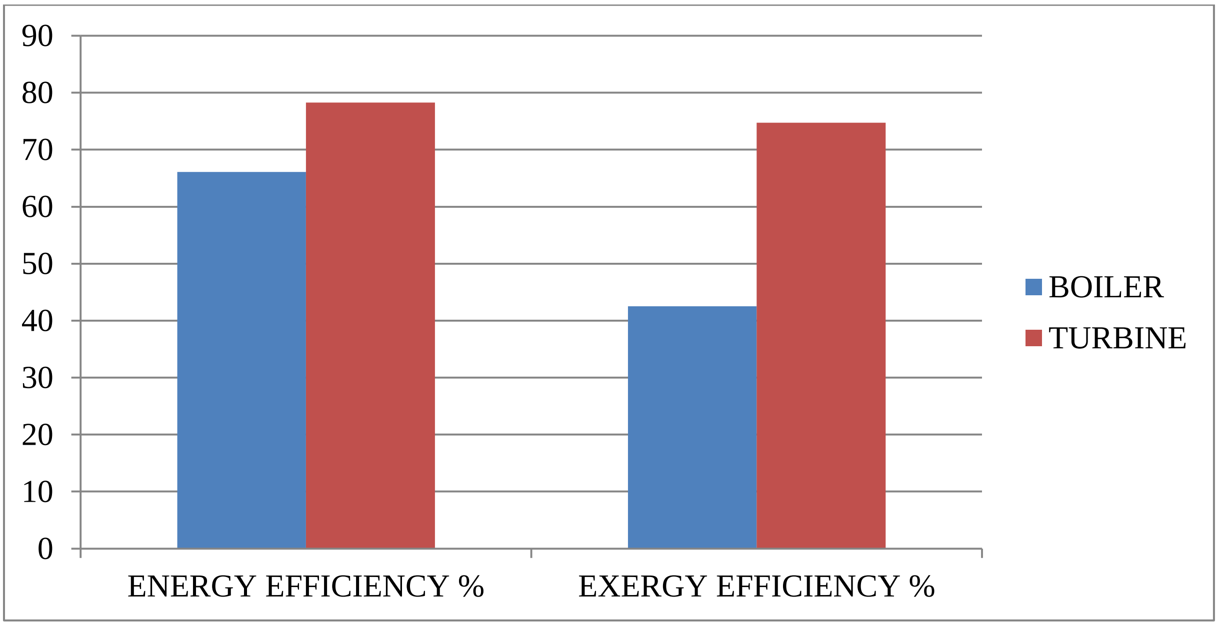

Comparision of energy and exergy efficiency

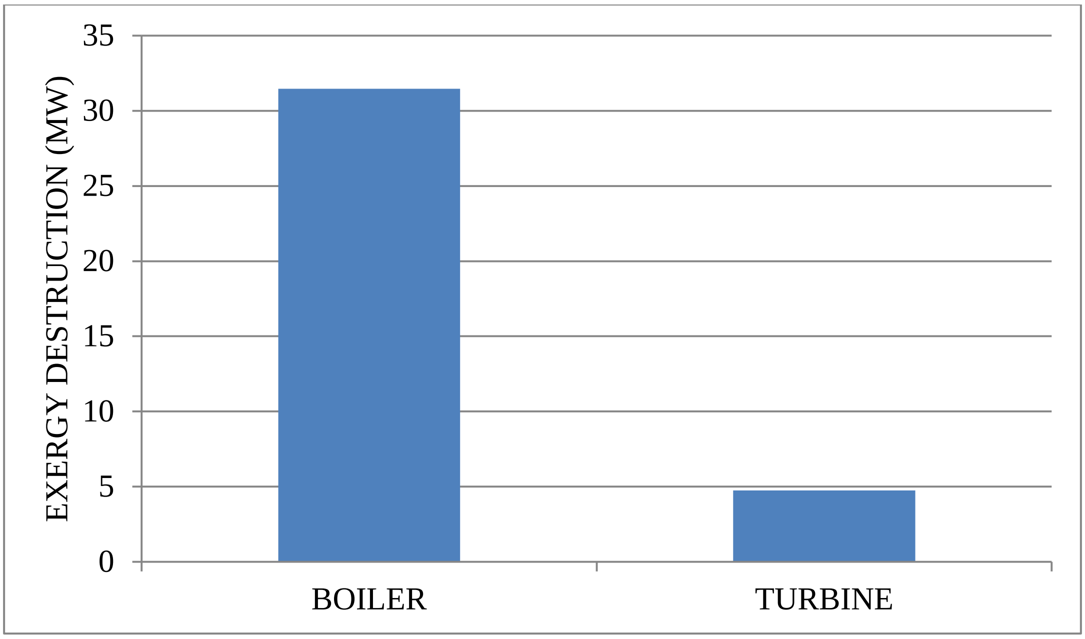

Table 5: Comparision of boiler and turbine

Component	Energy efficiency	Exergy efficiency	Exergy destruction
Boiler	66.08 %	42.55%	31.472 MW
turbine	78.26%	74.74%	4.756 MW

VI. CONCLUSION

From the energy and exergy analysis of cogeneration plant it is seen that energy analysis of boiler and steam turbine is 66.08 % and 78.26 % while exergy analysis is 42.55% and 74.74% respectively. There is a huge difference between energy efficiency and exergy efficiency. This difference exist due to large amount of energy degradation. This degradation of energy increases the entropy and hence a decrease in exergy. Thus first law analysis is the poor approximation of true efficiency. The second law analysis indicates the destruction of exergy. Therefore to increase the second law efficiency of the plant attempt should be made to reduce the destruction of exergy.

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Nomenclature:

C_p	Specific heat of superheated steam Kcal/kg
C_{pg}	Specific heat of flue gas Kcal/kg
m_{fg}	mass of dry flue gas kg/s
T_{fg}	Flue gas temperature °C
T_a	Ambient temperature °C
η_b	Efficiency of boiler
η_I	First law efficiency
η_{II}	Second law efficiency
Ψ_f	Exergy of fuel MW
Ψ_w	Exergy of feed water MW
Ψ_s	Exergy of steam formed MW
Ψ_a	Exergy of air MW
Ψ_{fg}	Exergy of flue gas MW
h_g	Enthalpy of steam formed KJ/kg
h_f	Enthalpy of feed water KJ/kg
S_g	Entropy of steam formed KJ/kgk
T_o	Reference temperature K
m_i	mass of inlet steam kg/s
h_i	Enthalpy of inlet steam KJ/kg
ε	emissivity
v	wind velocity m/s
F_{hr}	mass of fuel kg/hr
T_s	Surface temperature of furnace