Second Law Based Thermodynamic Analysis of Cogeneration Plant

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Abstract

The first law of Thermodynamics is used to analyze the energy utilization, but it is unable to account quality aspect of energy. The second law based thermodynamic analysis or exergy analysis assesses the energy on quantity as well as the quality and enables us to identify the magnitude and locations of real energy losses, to improve the existing systems or processes. The present paper deals with exergy analysis performed on an operating 23MW$_e$ unit of lignite and Indonesian coal fired cogeneration power plant at Nirma Limited, Bhavnagar. The exergy losses occurred in CFBC boiler combustor, heat recovery system and back pressure turbine have been calculated and distribution of the exergy losses during the real time plant running conditions has been assessed. The First law efficiency and the Second law efficiency of the components have also been calculated. The major exergy losses were found within the heat recovery system of the boiler.

1. Introduction

Energy consumption is one of the most important indicator showing the development stages of countries and living standards of communities. Population increment, urbanization, industrializing, and technologic development result directly in increasing energy consumption. This rapid growing trend brings about the crucial environmental problems such as contamination and greenhouse effect. Currently, 80% of electricity in the world is approximately produced from fossil fuels (coal, petroleum, fuel-oil, natural gas) fired thermal power plants, whereas 20% of the electricity is compensated from different sources such as hydraulic, nuclear, wind, solar, geothermal and biogas.

The purpose of this study presented here is to carry out energetic and exergetic performance analyses, at the design conditions, for the existing Coal and Lignite fired cogeneration plant in order to identify the needed improvement. For performing this aim, we summarized thermodynamic models for the considered power plants on the basis of mass, energy and exergy balance equations. Recently a large number of studies based on exergy analysis have been carried out by many researchers all over the world in various system applications.

Ganapathy et al. [1] determined the energy losses and the exergy losses of the individual components of the lignite fired thermal power plant. Exergy analysis results show that over 57% of exergy losses take place within the boiler system. Out of this, 42.7% of exergy loss occurs in the combustor only. This may be due to the irreversibility inherent in the combustion process, heat loss, incomplete combustion and exhaust losses. This pinpoints that the combustor requires necessary modification to reduce its exergy destructions thereby the plant performance can be improved. The exergy efficiency of the plant is 27%. But the results of energy analysis show that the major energy losses occurred in the condenser (39%) and the first law efficiency of the plant is 27%.

A. Rashad and A. El Maihy [2] performed an energy and exergy analysis of Shobra El-Khima power plant in Cairo, Egypt. The energy and exergy losses for the considered plant have been presented at different loads (Maximum load, 75% load and, 50% load). The maximum energy loss was found in the condenser. The percentage ratio of the exergy destruction to the total exergy destruction was found maximum in the Turbine system.

H. Ravi Kulkarni et al. [3] performed energy and exergy analysis of 32MW$_e$ coal fired thermal power plant at Surana power plant, Raichur, India. The results show that the major exergy losses occur in power plant are boiler, turbine and heat exchangers. There is 42% loss in boiler and 38% loss in turbine. The overall plant efficiency is 30%.

Pradeep Singh Hada and Ibrahim Hussain Shah [4] performed first and second law analysis of lignite fired 30MW$_e$ thermal power plant. The results show that in a boiler, the energy and exergy efficiencies are found to be 84.524% and 33.73% respectively. Irreversibilities (exergy destruction) for boiler is also calculated and found to be 93.355 MW which is the 67.90% of the total exergy input to the boiler. It has been found that the boiler is the major contributor for exergy destruction.

I. Satyanarayana et al. [5] discussed the exergy analysis of super critical power plant. Both first law efficiency and exergetical efficiency have studied at various pressure range between 200 bar to 425 bar and temperature range between 500°C to 800°C. The irreversibility and fractional exergy loss are determined for the cycle with and without reheat. It is concluded that exergy efficiency is high in reheat than non-reheat super critical cycle. It is found that nearly 20-25% irreversibility is reduced by using single reheat in the boiler, where as it is 12-15% in the turbine than the without reheating.

Kaushik et al. [6] discussed the comparison of energy and exergy analysis of thermal power plants stimulated by coal and gas. Furthermore, author provided a detailed review of different studies on thermal power plants over the years.

Marc A. Rosen [7] discussed energy and exergy based comparisons of coal-fired and nuclear electrical generating stations. Overall energy and exergy efficiencies, respectively, are 37% and 36% for coal-fired process, and 30% and 30% for the nuclear process.

R. Saidur et al. [8] conceptualized about energy and exergy utilization, and applied to the boiler system. Energy and exergy flows in a boiler have been shown and energy and exergy efficiencies have been determined and exergy destructions are compared with others work as well. Furthermore, several energy saving measures such as use of variable speed drive in boiler's fan energy savings and heat recovery from flue gas are applied in reducing a boiler energy use. It has been found that substantial amount of energy and money can be saved annually using VSD in boilers fan motor system. The study estimated that boilers fuel can be saved for a maximum of 8% energy savings using nanofluids and corresponding substantial bill savings with economically viable payback period.

I. Dincer et al. [9] discussed the analysis of energy and exergy utilization in the industrial sector of Saudi Arabia by considering the sectoral energy and exergy flows for a period of 12 years from 1990 to 2001. Oil and gas, chemical and petrochemical, iron and steel, and cement are identified as the four essential subsectors in the industrial sector. A comparison of the overall energy and exergy efficiencies of the Saudi Arabian industrial sector with the Turkish industrial sector is also presented for the year 1993.

Mark A. Rosen and Ibrahim Dincer [10] have pointed out the exergy of an energy form or a substance is a measure of its usefulness or quality or potential to cause change. A thorough understanding of exergy and the insights it can provide into the efficiency, environmental impact and sustainability of energy systems, are required for the engineer or scientist working in the area of energy systems and the environment. Exergy provides the basis for an effective measure of the potential of a substance or energy form to impact the environment and appears to be a critical consideration in achieving sustainable development.

In the present work, an exergy analysis has been performed on an operating 23MW$_e$ unit of lignite and Indonesian coal fired cogeneration power plant at Nirma Limited, Bhavnagar, Gujarat, India to find out the exergy losses in various components of plant. The energy and exergy efficiency of its individual components has been evaluated and also its energy losses are computed.

2. Description of cogeneration plant

A circuit diagram for boiler and turbine cycle with its various significant components, considered for the present study is shown in Fig. 1.

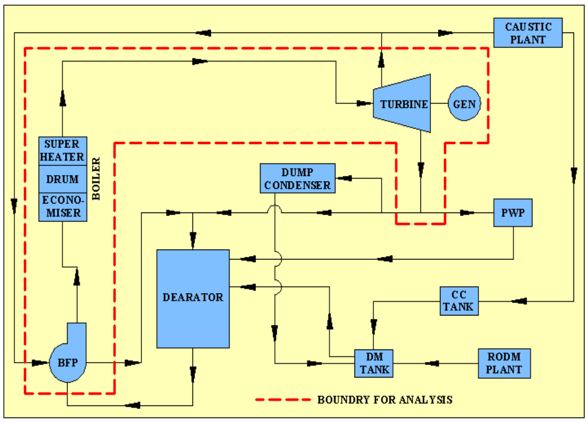

Fig. 1 Circuit diagram for boiler and turbine cycle

The energy and exergy calculation is limited up to a single unit of 200 TPH capacity boiler with 23 MW_e capacity back pressure turbine with no condenser at exhaust i.e. exhaust of 2.5 bar steam is directly given to chemical plant for process heating purpose. It is also having 35 bar of extraction for the same purpose of process heating as well as to run two boiler feed pumps. Continuous supply of de-mineralized water is ensured from RODM plant to the feed control station through dearator. The feed water enters to the boiler through feed control station and supplied to the economiser inlet header. After gaining heat in the banks of economiser, heated feed water further supplied to the hanger tube inlet header and further supplied to the steam drum through the hanger tube outlet header. Now, stored water from steam drum travels through down comer and reaches the combustor wall side tubes. The water in these tubes rises and exits out as a mixture of steam and water and enters in the drum by means of riser tubes where the steam is separated with the help of drum internals and supplied to the super heater. The super heated steam produced in the super heater then enters into the turbine through the main steam stop valve.

3. Methodology

The several components of the plant are grouped as boiler, heat recovery system, turbine and pumps. Fig. 1 indicates boundary limit for the analysis. The exergy analysis has been carried out for each component in the subsystems, to evaluate the exergy losses in the individual component and overall heat recovery system. The energy and the exergy losses of the components have been determined using their mass, energy and exergy balance equations. The exergy destructions for each component are then compared and presented. The energy and exergy efficiencies have also been computed for the individual components as well as for overall heat recovery system.

4. Exergy analysis

The exergy analysis is the combination of the First and Second laws of thermodynamics. In this analysis the heat does not have the same value as the work, and the exergy losses represent the real losses of work. When analysing novel and complex thermal systems, experience needs to be supplemented by more rigorous quantitative analytical tools. Exergy analysis provides those tools and it helps in locating weak spots in a process. This analysis provides a quantitative measure of the quality of the energy in terms of its ability to perform work and leads to a more rational use of energy. In general, the specific exergy denoted by "ε" is calculated using the equation as given below.

$$\varepsilon = \varepsilon_{k.e.} + \varepsilon_{p.e.} + \varepsilon_{ph} + \varepsilon_{ch} \tag{1}$$

Where, $\varepsilon_{k.e.}$ and $\varepsilon_{p.e.}$ are exergy due to velocity (or) kinetic energy and exergy due to potential energy respectively. ε_{ph} is physical exergy i.e. exergy due to temperature difference and pressure difference with respect to the reference point and ε_{ch} is chemical exergy (i.e due to reactions). In the present analysis, it is assumed that the exergy due to kinetic energy and potential energy are negligible. Also, for the exergy calculations, the atmospheric temperature and pressure are taken respectively as 34ºC and 101.325 kPa.

The energy losses $(\dot{Q})$ of the subsystem components are determined using the energy balances of the First law and similarly the exergy losses $(\dot{I})$ are calculated from the exergy balance equations of the Second law. Then using the energy losses the energy efficiency (the First law efficiency) is calculated and the exergy efficiency (the Second law efficiency) is determined using the exergy losses.

A. Combustor

The energy and exergy balance of the combustor is shown in the block diagram as per Fig. 2.

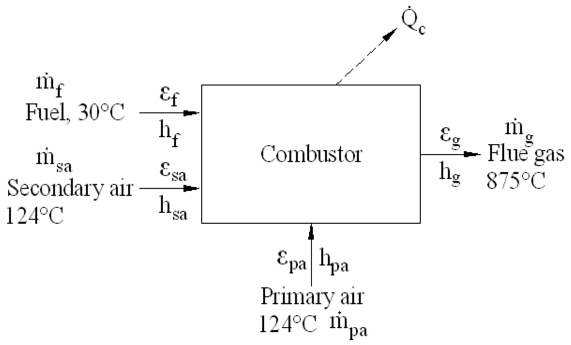

Fig. 2 Energy and exergy balance for combustor

For combustor, the mass, energy and exergy balances are

$$\dot{m}_f + \dot{m}_{pa} + \dot{m}_{sa} = \dot{m}_g + \dot{m}_{sg} \tag{2}$$

$$\dot{m}_f h_f + \dot{m}_{pa} h_{pa} + \dot{m}_{sa} h_{sa} = \dot{m}_g h_g + \dot{m}_{sg} h_{sg} + \dot{Q}_c \tag{3}$$

$$\varepsilon_f + \varepsilon_{pa} + \varepsilon_{sa} = \varepsilon_g + \varepsilon_{sg} + \dot{I}_c \tag{4}$$

$$\dot{m}_f (h_f - T_0 s_f) + \dot{m}_{pa} (h_{pa} - T_0 s_{pa}) + \dot{m}_{sa} (h_{sa} - T_0 s_{sa}) = \dot{m}_g (h_g - T_0 s_g) + \dot{m}_{sg} (h_{sg} - T_0 s_{sg}) + \dot{I}_c \tag{5}$$

B. Heat recovery system

The heat recovery system consists of super heater, economiser and air-preheater as shown in Fig. 3. The following equations are obtained from the mass, energy and exergy balances for the analysis of the heat recovery system.

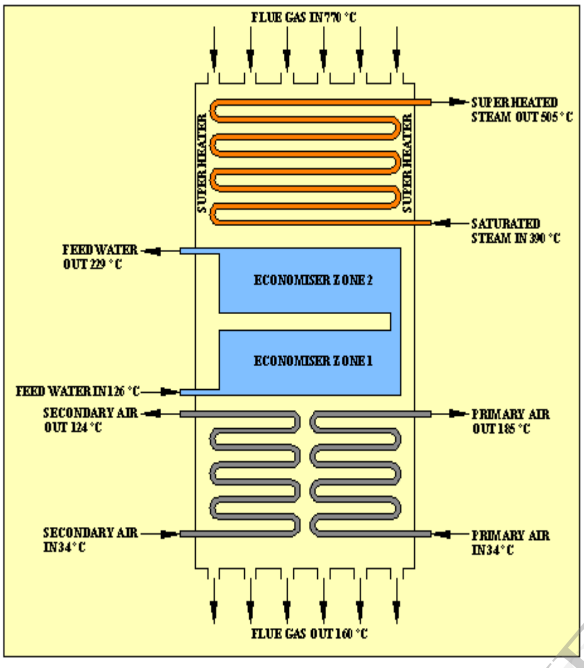

Fig. 3 Schematic diagram of heat recovery system

1. Super heater

Mass balance for gas side;

$$\dot{m}_{gi_{sup}} = \dot{m}_{go_{sup}} = \dot{m}_g \quad (6)$$

For steam side;

$$\dot{m}_{supi} = \dot{m}_{supo} = \dot{m}_{sup} \quad (7)$$

Energy balance;

$$\dot{m}_g(h_{gi} - h_{go}) = \dot{m}_{sup}(h_{supo} - h_{supi}) + \dot{Q}_{sup} \quad (8)$$

Exergy balance;

$$\varepsilon_{gi} - \varepsilon_{go} = \varepsilon_{supo} - \varepsilon_{supi} + \dot{I}_{sup} \quad (9)$$

$$\dot{m}_g[(h_{gi} - T_0 s_{gi}) - (h_{go} - T_0 s_{go})] =$$
$$\dot{m}_{sup}[(h_{supo} - T_0 s_{supo}) - (h_{supi} - T_0 s_{supi})] + \dot{I}_{sup} \quad (10)$$

2. Economiser

Mass balance for gas side;

$$\dot{m}_{gi_{eco}} = \dot{m}_{go_{eco}} = \dot{m}_g \quad (11)$$

For water side;

$$\dot{m}_{wi} = \dot{m}_{wo} = \dot{m}_w \quad (12)$$

Energy balance;

$$\dot{m}_g(h_{gi} - h_{go}) = \dot{m}_w(h_{wo} - h_{wi}) + \dot{Q}_{eco} \quad (13)$$

Exergy balance;

$$\varepsilon_{gi} - \varepsilon_{go} = \varepsilon_{wo} - \varepsilon_{wi} + \dot{I}_{eco} \quad (14)$$

$$\dot{m}_g[(h_{gi} - T_0 s_{gi}) - (h_{go} - T_0 s_{go})] =$$
$$\dot{m}_w[(h_{wo} - T_0 s_{wo}) - (h_{wi} - T_0 s_{wi})] + \dot{I}_{eco} \quad (15)$$

3. Air-preheater

Mass balance for gas side;

$$\dot{m}_{gi_{aph}} = \dot{m}_{go_{aph}} = \dot{m}_g \quad (16)$$

Energy balance;

$$\dot{m}_g(h_{gi} - h_{go}) =$$
$$\dot{m}_{pa}(h_{pao} - h_{pai}) + \dot{m}_{sa}(h_{sao} - h_{sai}) + \dot{Q}_{aph} \quad (17)$$

Exergy balance;

$$\varepsilon_{gi} - \varepsilon_{go} = (\varepsilon_{pao} - \varepsilon_{pai}) + (\varepsilon_{sao} - \varepsilon_{sai}) + \dot{I}_{aph} \quad (18)$$

$$\dot{m}_g[(h_{gi} - T_0 s_{gi}) - (h_{go} - T_0 s_{go})] =$$
$$\dot{m}_{pa}[(h_{pao} - T_0 s_{pao}) - (h_{pai} - T_0 s_{pai})] +$$
$$\dot{m}_{sa}[(h_{sao} - T_0 s_{sao}) - (h_{sai} - T_0 s_{sai})] + \dot{I}_{aph} \quad (19)$$

4. Overall heat recovery system

The overall heat recovery system of the plant is shown in Fig. 3. The energy and exergy losses are determined from the mass, energy and exergy balance equations given below. The First law efficiency and the Second law efficiency of the heat recovery system are calculated from these losses.

Mass balance;

$$\dot{m}_g = \dot{m}_{sup} + \dot{m}_w + \dot{m}_{pa} + \dot{m}_{sa} \quad (20)$$

Energy balance;

$$\dot{m}_g(h_{gi} - h_{go}) = \dot{m}_{sup}(h_{supo} - h_{supi}) + \dot{m}_w(h_{wo} - h_{wi}) +$$
$$\dot{m}_{pa}(h_{pao} - h_{pai}) + \dot{m}_{sa}(h_{sao} - h_{sai}) + \dot{Q}_{hrs} \quad (21)$$

Exergy balance;

$$\varepsilon_{gi} - \varepsilon_{go} = (\varepsilon_{supo} - \varepsilon_{supi}) + (\varepsilon_{wo} - \varepsilon_{wi}) +$$
$$(\varepsilon_{pao} - \varepsilon_{pai}) + (\varepsilon_{sao} - \varepsilon_{sai}) + \dot{I}_{hrs} \quad (22)$$

$$\dot{m}_g[(h_{gi} - T_0 s_{gi}) - (h_{go} - T_0 s_{go})] =$$
$$\dot{m}_{sup}[(h_{supo} - T_0 s_{supo}) - (h_{supi} - T_0 s_{supi})] +$$
$$\dot{m}_w[(h_{wo} - T_0 s_{wo}) - (h_{wi} - T_0 s_{wi})] +$$
$$\dot{m}_{pa}[(h_{pao} - T_0 s_{pao}) - (h_{pai} - T_0 s_{pai})] +$$
$$\dot{m}_{sa}[(h_{sao} - T_0 s_{sao}) - (h_{sai} - T_0 s_{sai})] + \dot{I}_{hrs} \quad (23)$$

C. Back pressure steam turbine

The energy flow of back pressure steam turbine is shown in Fig. 4. The mass, energy and exergy balances for the same is detailed in this section. The equations of energy balances for each component as given below are used to find out the energy losses whereas the exergy destructions are found out from the exergy balances.

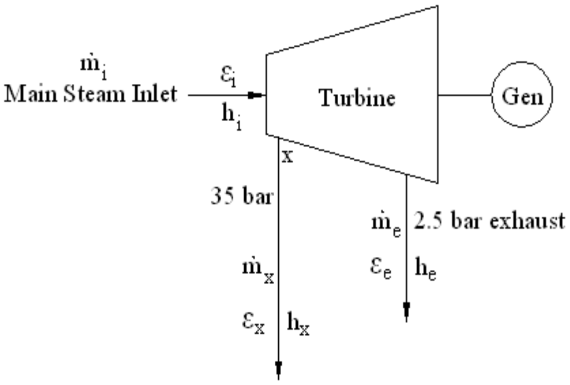

Fig. 4 Back pressure turbine energy flow

Mass balance;

$$\dot{m}_i = \dot{m}_x + \dot{m}_e \tag{24}$$

Energy balance;

$$\dot{m}_i h_i = \dot{m}_x h_x + \dot{m}_e h_e + \dot{Q}_{tur} \tag{25}$$

Exergy balance;

$$\varepsilon_i = \varepsilon_x + \varepsilon_e + \dot{I}_{tur} \tag{26}$$

$$\dot{m}_i (h_i - T_0 s_i) =$$

$$\dot{m}_x (h_x - T_0 s_x) + \dot{m}_e (h_e - T_0 s_e) + \dot{I}_{tur} \tag{27}$$

C. Feed pump

The mass, energy and exergy balances of the feed pump give the following equations to find out the energy and exergy losses. It can be noted that the exergy loss due to the heat loss from the pump at ambient temperature is zero because there is no heat transfer as pump has less temperature difference at inlet and outlet and whatever loss is due to the friction.

Mass balance;

$$\dot{m}_{fpi} = \dot{m}_{fpo} \tag{28}$$

Energy balance;

$$\dot{m}_{fpi} h_{fpi} = \dot{m}_{fpo} h_{fpo} + \dot{Q}_{fp} \tag{29}$$

Exergy balance;

$$\varepsilon_{fpi} = \varepsilon_{fpo} + \dot{I}_{fp} \tag{30}$$

$$\dot{m}_{fpi} (h_{fpi} - T_0 s_{fpi}) = (h_{fpo} - T_0 s_{fpo}) + \dot{I}_{fp} \tag{31}$$

5. Discussion

The operating data of the plant components such as combustor, super heater, economizer, air-preheater, feed pump and steam turbine of boiler E, Nirma Limited, Bhavnagar having 23MW$_e$ capacity, collected by one of the author and have been used for the present exergy analysis to calculate the enthalpies and exergies at different state points. The energy and the exergy losses of these components have been determined using the equations given in the previous section.

From the analysis, the overall heat recovery system energy losses and exergy losses are calculated as 18.22% and 59.47% respectively. The comparison of energy losses and exergy losses between different components is given in Fig. 5.

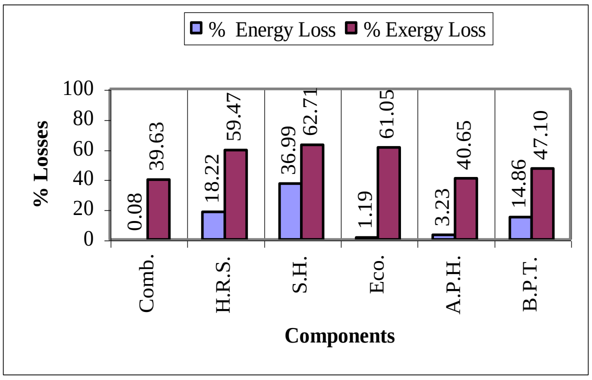

Fig. 5 Comparison between energy and exergy losses

It can be observed that maximum energy loss (36.99%) and exergy loss (62.71%) occurred in the super heater which is due to the fouling and damaging of certain portion in the super heater tubes. It can also be noted that whole heat recovery system is having 59.47% of exergy loss which demands for cleaning of fouled tubes and replacing the damaged tube with new one. It is also observed that the exergy loss (39.63%) occurred in the combustor which shows combustor is not fully adiabatic and combustion may not be completed. It is due to the irreversibility within the combustion process. This study pin points that the combustor requires necessary modification like refractory (insulation) modification to reduce exergy destructions thereby plant performance can be improved.

The variation in energy losses and exergy losses of back pressure turbine is shown in Fig. 6. It is due to the variation in stream flow at extraction and exhaust stage according to variation in plant demand of heat and electricity. It indicates good result compared to the boiler system because simultaneously it is developing high grade energy that is electrical power and it should be optimized between heat load and electrical load at given mass ratio for better operation and to minimize the variation between energy and exergy efficiency.

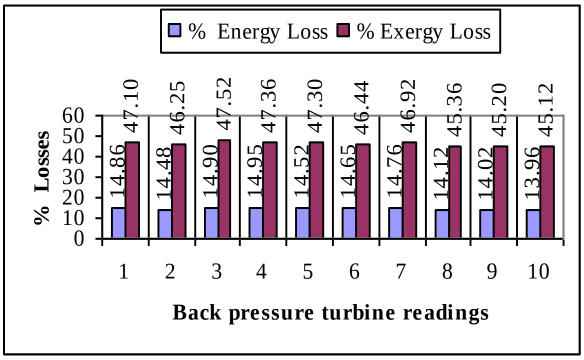

Fig. 6 Variation in energy and exergy losses of back pressure turbine

The First law efficiency (energy efficiency) and the Second law efficiency (exergy efficiency) of different components are also calculated and their comparison is depicted in Fig. 7.

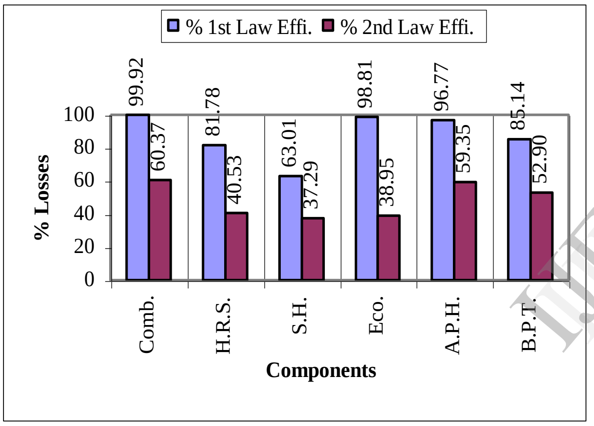

Fig. 7 1st law and 2nd law efficiency of the components

The 1st law efficiency and 2nd law efficiency of combustor is 99.92% and 60.37%, for heat recovery system it is 81.78% and 40.53%, for super heater it is 63.01% and 37.29%, for economizer it is 98.81% and 38.95%, for air-preheater it is 96.77% and 59.35% and for back pressure turbine it is 85.14% and 52.90% respectively. It can be noted that the there is a significant difference between energy efficiencies and exergy efficiencies. Thus the analysis of the plant based only on the First law principles may mislead to improve the plant output. Hence the First law analysis cannot be used to pinpoint prospective area for improving the efficiency of the cogeneration plant. However, the Second law analysis serves to identify the true inefficiencies occurring throughout the power station.

6. Conclusion

The Second law based thermodynamic analysis was performed on an operating boiler – E of Nirma Limited, Bhavnagar, having 23MWe capacity and the energy losses and the exergy destructions of the lignite and imported coal fired cogeneration power plant components have been calculated. Second law based analysis results show that the exergy efficiency is lower than the energy efficiency. The major exergy loss occurs in the heat recovery system i.e. super heater, economizer and air-preheater and the exergy loss in the heat recovery system is 59.47%. Out of this, 62.71% of exergy loss occurs in the super heater only, which leads to inefficient heat transfer between hot stream (flue gas) and cold stream (water & air). It indicates heat recovery system needs to be carefully inspected and necessary correction to be done. Thus the Second law based thermodynamic analysis locates the system or component where-in the necessary attention has to be paid to improve the performance of the plant.

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Nomenclature

MW_e	-	Mega watts electricity
CFBC	-	Circulating fluidized bed combustion
VSD	-	Variable speed drive
TPH	-	Ton per hour
RODM	-	Reverse osmosis & demineralization
ε	-	Specific exergy (KJ/Kg)
$\dot{Q}$	-	Heat loss or thermal energy loss (KJ)
$\dot{I}$	-	Exergy loss (KJ)
$\dot{m}$	-	Mass flow (Kg)
T_0	-	Environmental temperature (34°C)
h	-	Specific enthalpy (KJ/Kg)
BFP	-	Boiler feed pump
GEN	-	Generator
PWP	-	Pure water plant
CC	-	Condensate contaminated
DM	-	Demineralization
Comb.	-	Combustor
H.R.S.	-	Heat recovery system
S.H.	-	Super heater
Eco.	-	Economizer
A.P.H.	-	Air pre heater
B.P.T.	-	Back pressure turbine

Subscripts

k.e.	-	Kinetic energy
p.e.	-	Potential energy
ph	-	Physical
ch	-	Chemical
f	-	Fuel
pa	-	Primary air
sa	-	Secondary air
g	-	Fuel gas
sg	-	Steam generation
C	-	Combustor
i	-	Inlet
o	-	Outlet
gi	-	Gas inlet
go	-	Gas outlet
sup	-	Super heater
eco	-	Economizer
w	-	Water
aph	-	Air preheater
hrs	-	Heat recovery system
x	-	Extraction
e	-	Exhaust
tur	-	Turbine
fp	-	Feed pump