Exergy analysis and performance optimization of bagasse fired boiler

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Abstract. In the present scenario, the energy crisis and its demand have become the global problems that restrict the sustainable development. To overcome this problem, one needs to develop an advanced technological system which not only improves the system performance but also reduces the environmental effects. Several technologies have been established among which cogeneration appeared to be the most lucrative option. India, one of the leading producers of sugarcane, has enough cogeneration capacity in sugar mills. From the previous research articles, energy analysis explores several components which account for the significant loss of energy in a cogeneration power plant but the analysis based on the second law depicts that maximum exergy destruction occurred in a boiler. Hence, to enhance the overall performance of the plant, we need to improve boiler performance. In the present study, the energy and exergy analyses of a sugarcane bagasse boiler are carried out, and it has been seen that the energy efficiency of the boiler is high enough (81.78%). However, the second law efficiency is 25.08%, the irreversibility rate associated with the combustion chamber is 50.06 MW is a significant value which shows that 45.56% of the input fuel exergy is destroyed in the combustion chamber only. The irreversibilities associated with the heat exchangers are also significant which has been investigated as 17.23% of the input exergy of the fuel. This shows that the combustion chamber and heat exchangers both have enough scope of improvement.

Keywords: Bagasse, Cogeneration, Drying, Energy, Exergy, Sugar Industry.

1. Introduction
Thermal power generations are the primary source of electricity production in India. In general, power plant works on a low efficiency of nearly 40% and hence remaining 60% of the energy wasted into the environment. The significant loss during the cycle of operation is the heat rejection into the surrounding. These losses can be reduced by utilizing waste heat. There are several alternatives to recover and use the waste, and cogeneration is one of a lucrative option to improve the overall performance of the system.

Cogeneration can be defined as the combined generation of two different types of energy from a single primary energy input, especially thermal energy and mechanical energy. After that, this mechanical energy can be converted into electricity by installing an alternator, or it can be used for rotating various components such as a pump, compressor, fan, and motors. Thermal energy can be
utilized for direct process heating, or it can be indirectly used for producing steam or hot water, etc. Combined heat and power generation permits the energy of the fuel to be more efficient utilization than the separate generation of electricity and thermal energy. Independent electricity generation and heat utilization will consume more fuel as compared to the fuel required in cogeneration mode for the same power and heat generation. This would result in sustainable up-gradation of the existing system, along with the reduction in CO$_2$ emissions [1].

There are enough opportunities exists in various industries in India for simultaneous generation of electricity and thermal energy in cogeneration mode. India has an appropriate potential of about 15,000 MW electricity generation from the cogeneration mode in various core industries such as aluminium, sugar, fertilizer, paper & pulp, textile, cement, iron, and steel, rice mills, etc. The fuel burned for generating energy in cogeneration mode can be conventional fuels such as coal, diesel oil, gases, or renewable sources such as biomass-based fuels; bagasse, rice husk and biogas [2].

As per the law of conservation of energy, energy can’t be created nor can be destroyed, and it can only be converted from one form to another form. The better is the energy conversion process lower is the loss of energy [3]. Improving the performance of sugar industry-based cogeneration system reduces the consumption of petrol and diesel and hence reduces the greenhouse gas emissions [4]. Energy is the quantitative form which does not tell us the exact picture of the system. The better is the energy conversion process lower is the loss of energy. The thermal energy will give some work potential if the same has deviated from the dead state. The maximum useful extractable work from a system until it reaches in thermodynamic equilibrium with its surrounding is known as available energy or exergy. Exergy depends on system and surrounding both. The magnitude of available energy can be considered as a measure of the deviation of a system from its surrounding [5-6].

From the literature, a large number of papers have been studied to get various methods for increasing the power output and efficiency of cogeneration systems. There exist a large number of research articles which had been discussed about the energetic analysis of the cogeneration system. In present work, cogeneration in sugar industries has been considered, and data has been collected from the operating condition of bagasse fired boiler. Based on the received data, energy and exergy analyses of the same have been carried out to check the possible scope of further improvement. The number of papers which have been reviewed for the present work, the boiler has been observed the main component which is responsible for imperfections in the cogeneration system. Ravinder Kumar [7] investigated that a maximum portion of energy loss occurs in the condenser and next to the boiler. A boiler is the main component which contributed to the significant exergy destruction. He found that the exergy destruction cost in the boiler is more as compare to the exergy destruction cost in other parts of the system. Saidur et al. [8] investigated that combustor and heat exchanger is the main subsystems contributed to significant loss of the system. Loss of energy in the heat exchanger was found as 22.5% whereas exergy loss was found as 52%. This shows that there is high scope to improve the heat exchanger performance. Tapan et al. [9] proposed that increasing steam temperature and pressure will reduce the exergy losses and hence increases the exergetic efficiency. Terhan et al. [10] found first law and second law efficiencies of the boiler as 82% and 32.78% respectively. Similar characteristics were concluded by as concluded by Saidur et al. [8]. Due to heat loss and irreversibilities, significant losses occurred in the combustion chamber of a boiler [11-12]. Energy and exergy analysis of each component in boiler gives significant irreversibility rates (52 %) in the combustion chamber. The first law efficiency of the boiler comes out to be 60.3 %, whereas the exergy efficiency was only 19.9% [13].
Dincer et al. [14] found that the major portion of the exergy losses occurs in the combustion of a boiler, this shows that combustion chamber is the main component which is responsible for maximum entropy generation [15]. Inadequacy in power plants can also be examined by optimizing the area of heat exchangers. The balance between the size of hot and cold heat exchangers should be focused [16]. Barroso et al. [17] investigated the method of increasing the efficiency of a bagasse fired boiler. He obtains a simplified test code after extraction from complete regular test ASME and GOST methodologies. Optimal stack gas temperature was obtained in the range of 60-100 °C, and the scheme for optimum waste heat recovery was investigated as an economizer next to it an air preheater in the flue gas flow direction. Gurturk et al. [18] have done the energy and exergy analyses of a boiler in a cogeneration power plant. The first law and second law efficiency of the boiler were evaluated as 84.6% and 29.4%, respectively. It was investigated that 85.89% of the overall plant exergy destruction was contributed by the boiler alone. It was concluded that exergy destruction increases due to use of fuel having low combustion efficiency. Use of reheating and regenerator in steam turbine-based cogeneration system increases exergetic efficiency. Reheating the steam in cogenerative scheme increases the second law efficiency by 1.90%, whereas inclusion of regeneration increases it from 5% to 8%. Implementing both reheating and regeneration simultaneously increases second law efficiency from 5.9% to 8.45% [19].

Goran et al. [20] found that the boiler causes more than 80% of the total exergy destruction. Li et al. [21] have done advanced exergy analysis of a biomass boiler, and their results show that the maximum exergy destruction occurs during combustion and lowest in the Low-temperature superheater. Effect of bagasse moisture on exergy performance of the boiler has been investigated, and it was concluded that if moisture increased from 33% to 50% exergy efficiency reduced from 37.28% to 32.78% which means increasing moisture reduces heat content of the fuel.

2. Steam Generator

Fig. 1 shows the steam generation system consisting of
- Economizer
- Evaporator
- Superheater

![Figure 1. Line diagram for steam generation system and its subsystems.](image-url)
A boiler has an economizer, evaporator, and superheaters as their main subsystems. In starting, water enters into the economizer where it sensibly heated till the water reached boiling point. Further, water comes into the evaporator for latent heat exchange. Saturated steam leaves the evaporator exit, which passed through the superheater to superheat the steam until the turbine inlet condition [22]. A line diagram for the steam generation system (Fig. 1) has been developed to understand the detailed processes undergoing inside the boiler.

Also, the condition of steam at the exit of the turbine will have a negligible amount of moisture. The quality of steam at the exit of the turbine depends on the pressure ratio. The moisture in the last few stages of the steam turbine is not recommended since it can damage the turbine blades. But, more expansion of the steam till the condenser is desirable as it increases the plant thermal efficiency. Two types of superheaters are installed in this boiler, such as convective and radiant superheater. The radiant superheater is located near the exit of the furnace and faced direct incoming radiation from the furnace while convective superheater is situated away from the furnace and gets heat by the convection due to the moving flue gas passing through it [23]. Generally, sugar industries have enough fuel (bagasse) for burning during the steam generation process. However, it is the most effective and economical way to utilize the entire bagasse if the sugar mill has the generation capacity of more than 150 Mg per hour. For small capacity sugar mills, it is recommended to sell all the bagasse produced in the market [22].

3. Descriptions of the considered boiler

An average sugar factory in India is a co-generator, producing sufficient electricity through the topping cycle to meet its entire electricity requirement during the cane crushing season. The sugar factory-required steam at lower pressure for process heating & therefore, after producing steam in boilers at a higher pressure, the steam is consumed in a steam turbine for power generation and allowed to bleed the steam at the required pressure for process heating.

For the present work, a bagasse fired boiler has been considered, and energy and exergy analyses for the same have been performed. The boiler is a part of the steam generation system used in a Sugar Mill. The cogeneration plant at Ch. Devi Lal Co-operative Sugar Mills Ltd., Gohana is considered for the thermodynamic analysis. The crushing capacity of the plant is 2500 TCD but having an inbuilt capacity of 3000 TCD. The existing plant has 2 x 6 MW turbo-generator sets which has inlet steam pressure of 45 bar. The process steam requirement is at about 1.50 kg/cm$^2$. In addition to the above, the sugar plant will require about 5 Ton of steam per hour at 7.0kg/cm$^2$ for sulphur and centrifugal station, etc., and the steam necessary will be extracted from the back pressure-cum-extraction turbines.

The considered boiler has a steam generation capacity of 80 TPH with the outlet parameters of 45 bar & 415±/-12 °C with the feedwater inlet temperature of 105 °C. The feedwater temperature raised to 140 °C in an economizer. The steam parameters at the boiler outlet are 45 bar and 415 °C with the tolerance on the superheat temperature at + 12 °C. It has been assumed that whole bagasse produced by the plant will be consumed in the boiler, and total steam generated by the boiler will be passed through the turbines. The steam excess to the process requirements will be condensed through the condensing-cum-extraction turbines. The existing boiler has various components consisting of three main parts as mentioned above.

Considering 3000 TCD as the inbuilt capacity of the plant and average bagasse percentage on the cane as 32%, bagasse fired boiler is considered which consumed 40 TPH (11.11 kg/sec) of bagasse fuel generated during cane crushing process in the sugar mill. During the combustion analysis, 33.6% of excess air is taken. Water enters the evaporator at 45 bar and 258 °C and leaves as saturated steam at same pressure & temperature. The hot flue gases are further passed through the economizer where water is sensibly heated to its boiling point. Air preheater has been installed to recover the waste heat from the flue gas, and finally, these gases are allowed to exit through the stack. Flue gas temperature after heat recovery is 150 °C and temperature of the flue gas leaving the boiler is 145.28 °C.
4. Mathematical Modelling and Governing Equations
A boiler has specific accessories such as economizer, evaporator, and superheaters, etc. In the beginning, water enters into the economizer where it sensible heat transferred takes place till the water reached boiling point. Further, water comes into the evaporator for latent heat exchange. In the evaporator, saturated water converted to dry saturated steam at constant temperature and pressure. Saturated steam receivers at the evaporator exit passed through the superheater to superheat the steam until the turbine inlet temperature [24].

Refer to the T-s diagram in Fig. 2 for the boiler and its components; the following equations have been developed.

4.1 Energy Equations
4.1.1 Economizer
High-pressure feed water leaving the pump passes through the economizer for sensible heating. After heating, feed water goes to the evaporator. Heat absorbed by water in economizer is,

\[ Q_{eco} = m_w C_w (T_1 - T_2) \]  

4.1.2 Evaporator
In an evaporator, water converts into steam at constant temperature & pressure and absorbs the latent heat of vaporization.

\[ Q_{evap} = m_w h_{fg} \]  

4.1.3 Superheater
In superheater, saturated steam converts into superheated steam at constant pressure. Heat gained by steam is given by equation (3).

\[ Q_{sup} = m_s C_{ps} (T_4 - T_3) \]  

A total gain of energy in the boiler can be obtained by adding the equation (1), (2) & (3).

\[ Q' = m_w C_w (T_1 - T_2) + m_w h_{fg} + m_s C_{ps} (T_4 - T_3) \]

In the above equations, \( C_w \) and \( C_{ps} \) are the specific heat for water and specific heat of steam at constant pressure respectively, and \( h_{fg} \) is the latent heat of water at evaporator pressure.

4.1.4 Air preheater
In air preheater, the air is heated from ambient temperature to high temperature at constant pressure. Heat gain in the air is given by the following equation:

\[ Q_1' = m_a c_p a (T_a - T_0) \]

(5)

4.1.5 Boiler Efficiency (on NCV basis)

Thermodynamic analysis of sugarcane bagasse boiler is carried out. The work is presented using real data from a sugarcane bagasse boiler. Based on the energy and exergy analyses, the exergetic efficiencies and the irreversibility rates have been evaluated, and a summary of the results obtained is also presented.

Figure 3. Block diagram for energy distribution in the boiler [8].

Boiler efficiency based on NCV can be calculated from the formula mentioned below. Equation (6) shows the equation for boiler efficiency when there is no air preheater whereas equation (7) represents the case when air preheater is installed in the boiler.

Boiler efficiency without air preheater;

\[ \eta_{boiler} = \frac{q_1'}{m_f \text{ (NCV)}} \]

(6)

Boiler efficiency with air preheater;

\[ \eta_{boiler} = \frac{q_1'}{m_f \text{ (NCV)}-q_1'} \]

(7)

4.4 Exergy Equations

4.4.1 Assumptions

The following assumptions are taken to carry out the exergy analysis:

- The flue gases and air are assumed to be ideal gases.
- The kinetic and potential exergies are neglected.
- The incoming fuel temperature and pressure are considered as 25 °C and 1 atm, respectively.
- The reference state for water/steam is taken as a saturated liquid at a temperature of 25°C.
- Chemical exergy is considered as the only exergy which involves in the combustion process.

4.4.2 Exergy equations for Boiler

The temperature of the gas is evaluated using the energy balance equation for the combustion process. The combustion space has been taken considering the adiabatic chamber.

\[ m_f \text{ (NCV)} = \sum_k n_k h_{ph,k} \]

(8)

The term \( \sum_k n_k h_{ph,k} \) in the above equation can be evaluated from the values of \( h_{ph} \) from the Table D.1 given in Kotas [25]. To get the value of \( h_{ph} \), the temperature is required. With the help of iteration combustion temperature considering adiabatic space is found out 1225 °C. After that, exergy in the gas leaving the combustion chamber is evaluated using table A.3 and table D.3 from Kotas [25].

Irreversibilities associated with the combustion chamber, \( I_c = \varepsilon_f - \varepsilon_2 \)

Irreversibilities associated with the boiler;

\[ I = \varepsilon_f + \varepsilon_{air} + \varepsilon_w - \varepsilon_{exhaustgas} - \varepsilon_{steam} \]

(9)
Exergetic efficiency of the boiler; 
\[ \eta_{ex} = \frac{\epsilon_x - \epsilon_w}{\epsilon_{fuel}} = 1 - \frac{l}{\epsilon_{fuel}} \] (10)

Using equation (9) the irreversibilities rate inside the boiler has been evaluated. Higher is the irreversibilities rate lower is the second law efficiency. Exergetic efficiency or the second law efficiency of the boiler has been evaluated using equation (10). Though the irreversibility rate shows the inefficiency of the concern component, specific irreversibility could be a better option to compare the existing system with a similar process of another plant [26].

5. Results and Discussions

Based on the data collected for a bagasse fired boiler, detailed energy and exergy analyses have been carried out, and associated irreversibilities with the boiler its subsystems have been calculated. The energy utilized and the exergy exchange in each component of the boiler has been determined, and subsequently, the results have been presented in Tables. Boiler consists of two energy cycles; flue gas cycle and water/steam cycle. Flue gas cycle starts from grate where fuel burns till the exhaust of the gas from the stack. The temperature of the gases is evaluated from the energy balance during the combustion process considering adiabatic combustion. The burned gas temperature is found to be 1225 °C.

Water/steam cycle is a part of the Rankine cycle in which heat addition takes place at constant pressure in a boiler. High-pressure water at the exit of the pump is passed through the economizer for sensible heating. Almost saturated water is entered into the evaporator where latent heat transformation takes place which further superheated in the radiant and convective superheaters. The superheated steam at the exit of radiant superheater is then passed through a steam turbine for power generation.

5.1 Energy and Exergy Analysis of the boiler

Energy consumption and exergy change in each component of the boiler have been mentioned in Table.1 and Table. 2. Both the tables show that the maximum energy consumption and exergy exchange take place in the evaporator, whereas economizer consumed minimum energy.

Table 1. Energy and exergy distributions of the flue gases in a boiler (Flue gas cycle)

| Component | \( m_{fg} \) | \( \Delta E \) (kW) | \( \Delta X \) (kW) |
|-----------|--------------|---------------------|---------------------|
| RSH       | 55.06361     | 9252.89             | 6283.90             |
| CSH       | 55.06361     | 9173.32             | 6001.36             |
| Evaporator| 55.06361     | 46630.06            | 28773.19            |
| Economizer| 55.06361     | 12213.11            | 4519.85             |
| APH       | 55.06361     | 5957.88             | 1551.85             |

During the calculation of energy transfer, enthalpy at each state point of the fig. 2 has been taken from the steam table. For exergy change, entropy along with enthalpy values have been taken from the steam table. For exergy calculation, the environment has been considered as the reference point, which is a dead state.

Table 2. Energy consumed by water in each component of a boiler (Water/Steam cycle)

| Component | \( h_{in} \) (kJ/kg) | \( \Psi_{in} \) (kJ/kg) | \( \Delta X_{in} \) (kW) | \( h_{out} \) (kJ/kg) | \( \Psi_{out} \) (kJ/kg) | \( \Delta X_{out} \) (kW) |
|-----------|---------------------|------------------------|-------------------------|----------------------|------------------------|-------------------------|
| RSH       | 3035.76             | 1129.42                | 25095.81                | 3238.20              | 1230.90                | 27350.64                | 2254.83                |
| CSH       | 2791.64             | 1019.10                | 22644.54                | 3122.17              | 1173.19                | 26068.29                | 3423.75                |
Since the energy analysis does not explore the complete details of the system performance, and hence the second analysis has been performed. The component which shows the maximum associated irreversibility has enough scope for further improvement. Table 3, illustrates the exergy destruction in each component and it is seen that out of total exergy destruction which occurs in heat exchangers of this boiler evaporator contributes the maximum portion.

Table 3. Irreversibilities associated with the boiler and its subsystems

| Component      | $\Delta E$ (FG) (kW) | $\Delta E$ (W/S) (kW) | $\Delta X$ (FG) (kW) | $\Delta X$ (W/S) (kW) | I (kW) |
|----------------|----------------------|------------------------|-----------------------|------------------------|--------|
| RSH            | 9252.89              | 4498.21                | 6283.904017           | 2254.83                | 4029.074 |
| CSH            | 9173.32              | 7344.37                | 6001.357638           | 3423.75                | 2577.608 |
| Evaporator     | 46630.06             | 41967.14               | 28773.19              | 18513.60               | 10259.59 |
| Economizer     | 12213.11             | 10824.76               | 4519.825723           | 3370.80                | 1149.026 |

Further, a pie-chart in percentage consumption of energy has been constructed to get a clearer view of the energy distribution. Fig. 4 illustrates that 53.10% of the energy for steam generation contributed by the evaporator alone. Since the latent heat required for the phase transformation of water at lower pressure is very high. As we increase the boiler pressure, energy proportion in evaporator reduces due to a decrease in its latent heat. Improving the boiler pressure raises the boiling point, which further increases the exergy content of the steam leaving the boiler.

Figure 4. Percentage Energy utilized in the steam generator

The bar chart in fig. 5 illustrates the actual values of the energy utilized in each component of the boiler. The variations clearly show that the evaporator is the component which uses maximum energy of the fuel burned. As the boiler pressure is low, which leads to the higher value of its latent heat. This results in more energy consumption in the evaporator. Increasing the boiler decreases the latent heat of vaporization which reduces the energy consumption in the evaporator. Though improving the boiler pressure increases the heat content of steam in superheaters, and hence it enhances the turbine inlet condition. This increases the efficiency of the boiler as well as the overall system.
The first law analysis of sugarcane bagasse boilers gives the boiler efficiency high enough (81.78%). However, the irreversibility rate (I) which is defined as the substantial difference between inlet and outlet exergy flow rates, is 82.32 MW which shows that the exergy destruction in the boiler is too high and hence second law efficiency of the boiler is low, i.e., 25.08%. Out of the total irreversibility associated with the boiler, 45.56% exergy of the fuel is destroyed in the combustion chamber alone. In addition to exergy destruction in the combustion chamber, irreversibilities with the heat exchangers are significant which has been investigated as 17.23% of the input exergy of the fuel. This shows that the combustion chamber and heat exchangers both have enough scope of improvement.

5.2 Effects of bagasse moisture on energy and exergy distribution in the boiler

As the mill wet bagasse content 50% moisture which results in a large amount of energy wasted through the exhaust of the boiler. This also increases the volume of the flue gases, which lead to a change in the size of the heat exchanger. In the present analysis, it has been found that 14691.90 kW of energy is wasted into the environment from the exhaust which shows the 18.59% of the input fuel energy has been lost into the atmosphere due to moisture present in bagasse.

| Moisture content in bagasse (%) | Exergy loss due to moisture in bagasse (kW) | Energy loss due to moisture in bagasse(kW) | Percentage Exergy loss | Percentage Energy loss |
|---------------------------------|-------------------------------------------|------------------------------------------|-----------------------|-----------------------|
| 50                              | 2634.175                                  | 14691.86                                 | 2.51956854            | 18.58938512           |
| 45                              | 2370.757                                  | 13222.68                                 | 2.26761168            | 16.73044661           |
| 40                              | 2107.34                                   | 11753.49                                 | 2.0156483             | 14.8715081            |
| 35                              | 1843.922                                  | 10284.3                                  | 1.76369797            | 13.01256959           |
| 30                              | 1580.505                                  | 8815.118                                 | 1.51174112            | 11.15363107           |
| 25                              | 1317.087                                  | 7345.932                                 | 1.25978427            | 9.294692562           |
| 20                              | 1053.67                                   | 5876.746                                 | 1.00782741            | 7.43575405            |
| 15                              | 790.252                                   | 4407.559                                 | 0.75587056            | 5.576815537           |
Drying of bagasse could be a better approach to improve the performance of the boiler, which will further enhance the overall performance of the cogeneration system [27]. The reduction of cane bagasse moisture increases the lower heating value of the fuel, and at the same time, the volume of the flue gases leaving the boiler is reduced. The specific heat of water vapor is almost twice that of other gases, and hence the heat losses by flue gases are reduced [28].

**Figure 6.** Effect of % bagasse moisture reduction on a loss of energy in the exhaust

Fig.6 highlighting the advantage of bagasse drying, as the percentage moisture content in bagasse decreases the loss of energy through the exhaust of the boiler decreases and therefore, we can save more energy when the fuel has lower moisture content (as shown in Fig 7).

**Figure 7.** Effect of % moisture reduction in bagasse on energy saved in the exhaust
Reducing the moisture from 50% to 15% will save 12.68 MW of energy, this contributes 13% of the input fuel energy. However, 1.76% of the input fuel exergy can be saved for the same moisture reduction. Varying moisture content changes the energy and exergy loss in the exhaust. From the graph, it is clear that presence of moisture contributes a large amount of energy loss, however, the work potential of this loss is quite low due to the low temperature of the stack gases. However, another drawback of the moisture is the large volume of the flue gases, which will further affect the size heat exchanger. Drying will reduce the volume of the exhaust gases leaving the stack, and it improves the overall performance of the system.

Drying can be done by various methods such as passing the part of the flue gases coming from the economizer through the dryer, and another way of drying is open sun drying; keeping the bagasse into the open environment. In spite of the open sun drying is cheaper and easily accessible, but it takes a longer time. However, flue gas drying takes lesser time, but it does at the cost of energy of the flue gas. When the percentage bagasse moisture decreases to 30%, a significant amount of energy gain was noticed. Drying was achieved after passing the flue gasses through the bagasse dryer [29]. In another paper [30], the characteristics of thin layer olive bagasse drying were investigated. Various drying conditions such as temperatures ranging from 125 °C to 250 °C, relative humidity and gas velocity were taken for studying the terms of combustible gases. It was recommended that the drying temperatures should be kept below 250 °C for safer drying to prevent pyrolysis of the olive bagasse.

Compromising the energy of the flue gases for drying will reduce its combustion air temperature, which will further reduce the energy available for air preheater and hence the overall efficiency of the plant. There is a need to conduct a detailed comparative analysis which could explore some alternative way to solve this problem.

6. Conclusions
In the present study, detailed energy and exergy analyses of a bagasse fired boiler have been carried out. The boiler which has been considered for the investigation has the steam generation capacity of 80TPH with the outlet parameters of 45 bar & 415°C. The fuel is a by-product of a sugar mill operating with the cane crushing capacity of 3000 TCD. The main remarks which have been concluded from the current study are listed below.

- Energy analysis reveals that the energy efficiency of the boiler is 81.78%. However, the second law efficiency is quite low 25.08%, which shows that the entropy generation in the boiler is too high.
The irreversibility rate associated with the combustion chamber is found as 50.06 MW. This shows that the combustion chamber itself destroys 45.56% of the input exergy of the fuel. In addition to exergy destruction in the combustion chamber, irreversibilities with the heat exchangers are also significant, which has been investigated as 17.23% of the input exergy of the fuel. This deduces that the combustion chamber and heat exchangers both have enough scope of improvement.

The moisture reduction in mill wet bagasse increases the lower heating value of the fuel along with the decrease in the volume of the flue gases leaving the boiler. In the current study, it has been found that 14691.90 kW of energy is wasted into the environment through the boiler exhaust, which contributes 18.59% of the input fuel energy.

Reducing the moisture content from 50% to 15% will save 12.68 MW of energy, this contributes 13% of the input fuel energy. However, 1.76% of the input fuel exergy can be saved for the same moisture reduction. Though the exergy loss is more, the moisture will release the large volume of the flue gases, which will further affect the size of the heat exchanger and hence the overall performance of the system.

Further work is required to reveal the causes of the massive loss in the combustion chamber and to check the economic opportunities for decreasing it. It is also necessary to explore the various alternatives for drying the mill wet bagasse before supplying for the combustion process.

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