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ENERGY AND EXERGY ANALYSIS OF BOILER IN BAGASSE BASED 20 MW STEAM POWER PLANTS

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Abstract:

In present study energy and exergy analysis has been applied to baggasse based 20 MW steam power plant. The energy losses at various locations in power plant have been calculated by applying energy balance. Rate of exergy destruction or irreversibility in different components of power plant are calculated by applying exergy balance. It is found that energy losses in boiler and condenser are equal and around 95% of total energy losses in power plant. The irreversibility rates of the boiler are found to be much higher than the irreversibility rates of the other components. First law efficiency and second law efficiency of boiler are calculated. The changes of the irreversibility rates of boiler with the ambient temperature (for range 278-313K) are studied. As the ambient temperature is increased from 278 to 313 K, the irreversibility rates of the boiler also increase. The calculations for efficiencies of steam power plant based on first law of thermodynamics and second law of thermodynamics have been calculated at ambient temperature of 298 K and values are found to be 23.82% and 19.48% respectively.

1. INTRODUCTION

Recently, exergy analysis has become a key aspect in providing a better understanding of the process, to quantify sources of inefficiency, to distinguish quality of energy (of heat). Exergy is defined as the maximum theoretical useful work obtained as a result of interaction of system with a reference environment. Exergy is only conserved for a reversible process, but it is partly consumed in an irreversible process. Thus, exergy is never in balance for real processes. For a real process, the exergy input always exceeds the exergy output; this imbalance is due to the exergy destruction. Exergy destruction is a measure of irreversibility that is the source of performance. Therefore, an exergy analysis assessing the magnitude of exergy destruction identifies the location, magnitude and the sources of thermodynamic inefficiencies in a thermal system. This provides useful information for the improving the overall efficiency and cost effectiveness of a system and comparing the performance of two systems. Exergy analysis usually predicts the thermodynamic performance of an energy system and the efficiency of the system components by accurately quantifying the entropy generation within components.

Kaushik et al. [3] did energy and exergy analysis of coal fired power plant operating on Rankine cycle and found that maximum energy loss occurred in the condenser and the maximum exergy losses occurred in the boiler. Ganapathy et al. [4] conducted exergy analysis of 50MWe lignite fired thermal power station of Neyveli Lignite Corporation Limited, Neyveli, Tamil Nadu, India. The comparison between the energy losses and the exergy losses of the individual components of the plant shows that the maximum energy losses of 39% occur in the condenser, whereas the maximum exergy losses of 42.73% occur in the combustor. Saidur et al. [5] studied energy, exergy efficiency, energy losses, and exergy destruction for a boiler and suggested and ways to reduce boiler energy consumption by using variable speed drive. In a boiler, the energy and exergy efficiencies were found to be 72.46% and 24.89%, respectively. Mehdi et al. [6] analyzed a thermal power plantwith use of energy and exergy concept. Horlock et al. [7] estimated the rational efficiencies of three modern fossils-fuel power plants using the exergy calculations. They analyzed the effect of water or stream injection on the rational efficiency of the plant. The relation between the irreversibility in combustion and the loss of exergy due to mixing in the exhaust was also considered in their analysis. Various researchers applied exergy analysis to process in the hydrogen and hydrogen fuels, advanced power plants [8-13]. Dincer and Rosen [14] presented effects of variation in dead-state properties, and involves two main tasks: (1) Examination of the sensitivities of energy and exergy values to the choice of the dead-state properties and (2) analysis of the sensitivities of the result of energy and exergy analyses of complex systems to the choice dead-state properties. Kamate and Gangavat [15] studied exergy analysis of bagasse – based cogeneration plant of atypical 2500 TCD sugar factory, using backpressure and extraction condensing steam turbines.

2. ENERGY BALANCE

Energy is always conserved so that the energy entering must be equal to the sum of the energy stored within the system and the energy flowing out from the system. This energy balance can be expressed as follows:

Energy input – Energy output = Energy stored

Therefore,

$E_{in} – E_{out} = dE$ (kJ) (1)

The energy balance reduces for steady-flow process to

$\dot{E}_{in} – \dot{E}_{out} = dE_{system}/ dt$ (kW) (2)

or

Rate of Net energy change in transfer by heat, work and mass	=	Rate of change in internal, kinetic, potential etc. energieS

But for steady-flow process, $dE_{System}/dt = 0$

or

Therefore,

Energy balance: $\dot{E}_{in} = \dot{E}_{out}$ (kW) (3)

The energy or first law efficiency, η_I

The energy or first law efficiency of a system and/or system component is defined as the ratio of energy output to the energy input to system/component i.e.

$$\eta_I = \frac{\text{Desired output energy}}{\text{Input energy supplied}} \quad (4)$$

Exergy

A system delivers the maximum possible work as it undergoes a reversible process from the specified initial state to the state of its surrounding environment, that is, dead state. This represents the useful work potential of the system at the specified state and is called exergy. It is important to realize that exergy does not represent the amount of work that a work producing device will actually deliver upon installation. Rather, it represents the upper limit of amount of work a device can deliver without violating any thermodynamic laws [1].

The energy of the universe is constant, but exergy is constantly consumed. The second law of thermodynamics tells us that the quality of energy is degraded in every process. This means that the quality of the energy in the universe as a whole is constantly diminishing. This “energy quality” has been named as exergy. Thus, other name for the second law could be “Exergy Law”.

Exergy by heat transfer, Q

$X_{heat} = (1 – T_o/T)$ Q (5)

Exergy transfer by work, W

X_{work}= W (6)

Exergy transfer by mass, m

Mass flow rate is a mechanism to transport exergy, entropy and energy into or out of a system. When mass in the amount of m enters or leaves a system, exergy in the amount of mψ, Where, ψ is called flow (or stream) exergy for unit mass of stream.Flow exergy for unit mass:

$\psi = (h – h_o) – T_o(s – s_o) + V_2/2 + gz$ (7)

When the changes in kinetic and potential energies are negligible, then equation (1.13) becomes

$\psi = (h – h_o) – T_o(s – s_o)$ (1.14)

Exergy transfer by mass:

$X_{mass} = m\psi$ (8)

Therefore, the exergy of a system increases by mψ when mass in the amount of m enters, and decreases by the same amount when the same amount of mass at the same state leaves the system.

The decrease of exergy principle and exergy destruction:-

The exergy of an isolated system during a process always decreases or, in the limited case of a reversible process, remains constant. In other words it never increases and exergy is destroyed during an actual process. This is known as decrease of exergy principle.

The exergy destroyed is proportional to the entropy generated and can be expressed as

$$X_{destroyed} = T_o S_{gen} \geq 0 \quad (9)$$

Where T_o is the ambient temperature. Exergy destroyed is a positive quantity for any actual process.

Exergy destroyed represents the lost work potential and is also called the irreversibility or lost work [1]. Positive direction is taken for heat transfer to the system and for work transfer from the system. Therefore,

$dX/dt = \dot{X}_{heat} - \dot{X}_{work} + \dot{X}_{mass(in)} - \dot{X}_{mass(out)} - \dot{X}_{destruction}$ (10)

or

$dX/dt = \sum(1–T_o/T)\dot{Q} – \dot{W} + \sum \dot{m}\psi_{in} – \sum \dot{m}\psi_{out} – \dot{X}_{destruction}$ (11)

Exergy balance for steady-flow system

Most control volumes encountered in practice such as turbines, compressors, nozzles, diffusers, heat exchangers, pipes, and ducts operate steadily, and thus they experience no changes in their mass, energy, entropy, and exergy contents as well as their volumes. Therefore, dX/dt = 0 for such systems, and the amount of exergy entering a steady flow system in all forms (heat, work, mass transfer) must be equal to the amount of exergy leaving plus the exergy destroyed. Then the rate form of the general exergy balance (Eq. 1.19) reduces for a steady-flow process to

Steady-flow:

$\dot{X}_{destruction} = \sum(1–T_o/T)\dot{Q} – \dot{W} + \sum\dot{m}\psi_{in} – \sum\dot{m}\psi_{out}$ (12)

Second law efficiency or Exergetic efficiency of steady flow devices, η_{II}

The second law efficiency is defined as:

η_{II} = Exergy output/Exergy input

=1–Exergy destruction/Exergy input (13)

In the present study, energy and exergy analysis were performed for baggase based steam power plant. Mass and energy conservation laws were applied to major components of the power plant system. Quantitative exergy balance for each component was considered. In this study, the effect of ambient temperature on exergy destruction in each component was calculated.

3 DESCRIPTION OF STEAM POWER PLANT

In present study, energy and exergy analysis of baggase based 20 MW steam power plant located at Village Sugauli, District East Champaran, Bihar have been performed. A schematic diagram of the plant with its various significant components such as a boiler (B), Turbine (T), a condenser (C), a de-aerator (D), feed water pump (FWP), feed water heaters (FWH2 & FWH1), a generator (G), is shown in Fig 1. It is regenerative feed water heating arrangement. The steam turbine is triple extraction cum condensing turbine. The steam is extracted at three intermediate stages (9, 12 and 15) at appropriate pressure and temperature. The exhaust from turbine is condensed in condenser. The steam extracted at stage 9 and 12 is utilized in feed water heaters FWH1 and FWH2. The extraction at stage 15 is utilized in de-aerator. Condensate from condenser (2), FWH1 (11), FWH2 (14) return to de-aerator for the continuation of the cycle. Feed water is heated in FWH2 and FWH1.Mass balance at de-aerator results in quantity of make-up water used

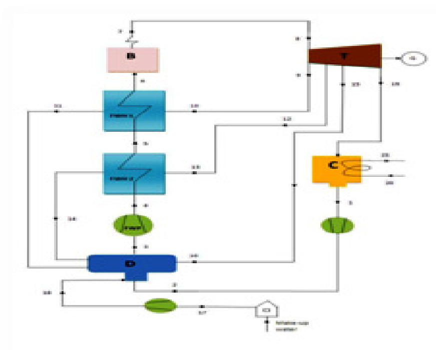

Fig. 1 Schematic diagram of steam turbine power plant

Table :1 Operating values of the power plant.

Parameters	value
Power input to feed water pump , $\dot{W}_F W_P$	410.3 kW
Power output of steam turbine , $\dot{W}_T$	20000 kW
Temperature of hot products of combustion in combustor (TP)	1403K
Temperature of flue gases, (Tg)	453K
Thermal efficiency of boiler, η_B	70%

4 ENERGY AND EXERGY ANALYSIS – MATHEMATICAL FORMULATIONS

Traditional methods of thermal system analysis are based on the first law of thermodynamics. Traditional analysis uses an energy balance on the system to determine heat transfer between the system and its environment. The first law of thermodynamics introduces the concept of energy conservation, which states that energy entering into a thermal system with fuel, electricity, streams of matter entering/leaving, and so on is conserved and cannot be destroyed [16]. In general, energy balance provides no information on the quality or grades of energy crossing the thermal system boundary and no information about internal thermal losses. In contrast to the first law of thermodynamics, second law of thermodynamics introduces the useful concept of exergy in the analysis of thermal system. Exergy is a measure of the quality or grade of energy and it can be destroyed in the thermal system. The second law states that part of the exergy entering into a thermal system with fuel, electricity, flowing streams of matter, and so on is destroyed within the system due to irreversibility. The second law of thermodynamics uses an exergy balance for the analysis and the design of thermal systems. Subsequent sections contain mathematical formulations used to carry out the energy and exergy balance of components of baggase based steam power plant.

4.1 Theoretical approach

The bagasse based power plant has different major components and energy and exergy analysis have been applied to these components. Analysis is based on following assumptions:

- Steady state operating conditions exits.
- Kinetic and potential energies are neglected.
- The ambient conditions of temperature and pressure are 25˚C 1nd 1.013 bar.
- The exergy loss due to heat loss from the each component to environment (at ambient temperature) is zero.
- Exergy of fuel (bagasse) ψ_f remains constant with the change of ambient temperature.
- The value of specific heat Cp and entropy of gases and air is taken constant.
- The drop in temperature of hot products of combustion combustor to heat exchanger is zero.
- The unburned losses are negligible.
- Blow down in the boiler was neglected

4.2 Analysis of bagass

Bagasse is often used as a primary fuel for sugar mills, when burned in quantity; it produces sufficient heat energy to meet all the power requirement of a sugar plant, with energy to spare. To this end, a secondary use for this waste product is in cogeneration, the use of a fuel source to provide both heat and electricity in sugar plant. Bagasse composition is function of the following factors: cane characteristics, soil type, season, juice extraction method. In this thesis an average composition of 23.5% of carbon, 3.25% of hydrogen, 21.75% of oxygen, 1.50% of ashes and 50% of moisture is considered.

Table:2 Bagasse Composition

Constituent	Weight of constituents in 1 kg of Bagasse (kg.)	Combustion Reaction	Weight of O2 required (Kg)
C	0.235	C+O2 = CO2	0.235 x 32/12 = 0.627
H	0.0325	H2 + (1/2)O2 = H2O	0.0325 x 16/2 = 0.260
O	0.2175		
Ash	0.015		
Moisture	0.50		

4.3 Calculations for energy analysis and exergy analysis

A boiler can be divided into combustor and heat exchanger as shown in Fig:2 .The energy and exergy analysis of these two parts have been presented below.

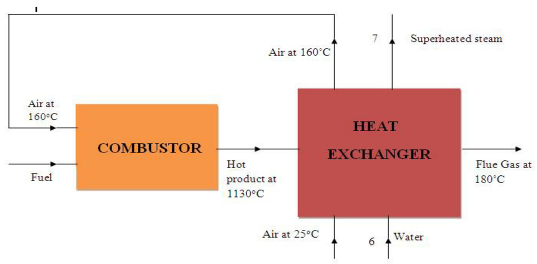

Fig.2 Schematic diagram of boiler

Table: 3 Operating parameters of combustor and heat exchanger

Parameters	Value
Mass flow rate of air (ṁa)	40.75 kg/sec
Mass flow rate of fuel (bagasse) (ṁf)	10.37 kg/sec
Mass flow rate of hot product produces by combustor (ṁp)	51.12 kg/sec
Mass flow rate of flue gases (ṁg)	51.12 kg/sec
Enthalpy of fuel (bagasse) i.e. Lower calorific value (LCV) of fuel (bagasse) (hf)	7929 kJ/kg
Specific exergy of fuel (bagasse)(ψf)	9959 kJ/kg
Temperature of hot product produces by combustor (TP)	1403 K
Temperature of flue gases (Tg)	453 K
Enthalpy of hot product produces by combustor (hp)	1764.02 kJ/kg
Enthalpy of flue gases (hg)	506.91 kJ/kg
Specific entropy of hot product (sp)	8.97 kJ/kg.K
Specific entropy of hot product at ambient temperature 25oC (so)P	7.026 kJ/kg.K
Specific entropy of flue gases (sg)	7.5 kJ/kg.K
Specific entropy of air at 160oC (sa)@160oC	2.07 kJ/kg.K
Specific entropy of air at 25oC (so)a@25oC	1.695 kJ/kg.K
Enthalpy of air at 25oC at inlet of heat exchanger (ha)@25oC	298.18 kJ/kg
Enthalpy of air at 160oC at inlet of combustor (ha)@160.1oC	434.38 kJ/kg
Specific heat of air at ambient temperature (298K) (Cp1)	1.00 kJ/kg.K
Specific heat of hot product at ambient temperature (298K) (Cp2)	1.102 kJ/kg.K

Combustor Energy analysis

Rate of energy in = $\dot{m}_a(h_a)@160^oC + \dot{m}_f h_f$

Rate of energy out = $\dot{m}_p h_p$ + rate of energy loss

The energy flow for steady flow process of an open system is given by

Rate of energy in = Rate of energy out

$\dot{m}_a(h_a)@160^oC + \dot{m}_f h_f = \dot{m}_p h_p$ + rate of energy loss

Rate of Energy loss $=\dot{m}_a(h_a)@160^oC + \dot{m}_f h_f = \dot{m}_p h_p$

Rate of Energy loss $=\dot{m}_a h_a@160^oC + \dot{m}_f h_f - \dot{m}_p h_p$

$=40.75\times434.38 + 10.37\times7929 - 51.12\times1764.02$

= 99924.71 – 90176.70

= 9748.01 kW

$\eta_{I(Combuster)}$ =1–rate of energy loss/rate of energy in

= 1–rate of energy loss/$\dot{m}_a(h_a)@160^oC + \dot{m}_f h_f$ (4.18)

$\eta_{I(Combuster)}$=1–Rate of Energy loss/$\dot{m}_a h_a@160^oC + \dot{m}_f h_f$

= 1 – 9748.01/99924.71

= 90.24%

Combustor Exergy analysis

ψ: specific exergy flow in kJ/kg

$\psi = (h - h_o) - T_o(s - s_o)$

$= (h - T_o s) - (h_o - T_o S_o)$

It can be noted that the rate of exergy loss due to the heat loss from the combustor (at ambient temperature) is zero.

The rate of exergy destruction for a steady flow process of an open system is given by

$\dot{X}_{destruction} = \dot{m}_a\psi_a@160^oC + \dot{m}_f\psi_f - \dot{m}_p\psi_p$

Putting the value of ψ,

$\dot{X}_{destruction}=\dot{m}_a[(h_a-h_o)-T_o(s_a-s_o)]Air@160^oC + \dot{m}_f\psi_f - \dot{m}_p[(h_p-h_o) - T_o\{s_p - (s_o)_p\}]]$

$=\dot{m}_a(h_a)@160^oC - \dot{m}_a T_o(CP_1 + s_a - s_o)Air@160^oC + \dot{m}_f\psi_f - \dot{m}_p h_p + \dot{m}_p T_o[CP_2 + s_p - (s_o)_p]$

$=40.75\times434.38 - 40.75\times298(1.0 + 2.07 - 1.695) + 10.37\times9959 - 51.12\times1764 + 51.12\times298(1.102 + 8.97 - 7.026)$

= 60498.81 kW

Combustor Second law efficiency or exergetic efficiency

$\eta_{II(Combuster)}$=1–rate of exergy destruction/rate of exergy in

$=1-\dot{X}_{destruction}/\dot{m}_a[(h_a-h_o)-T_o(s_a-s_o)]Air@160^oC + \dot{m}_f\psi_f$

$\eta_{II(Combuster)} = 1 - \dot{X}_{destruction}/\dot{m}_a[(h_a - h_o) - T_o(s_a - s_o)]Air@160^oC + \dot{m}_f\psi_f$

$= 1 - 60498.81/40.75[(434.38 - 298.18) - 298(2.07 - 1.695)] + 10.37\times9959$

= 1 – 60498.81/996.33 + 103274.83

= 41.98%

Heat exchanger Energy analysis

As, $\dot{m}_p = \dot{m}_g$ and $\dot{m}_6 = \dot{m}_7$

Rate of Energy in = $\dot{m}_p(h_p - h_g)$

Rate of Energy out $=[\dot{m}_6(h_7-h_6) + \dot{m}_a\{(h_a)Air@160^oC - (h_a)Air@25^oC\}]$+Rate of Energy loss

The energy flow for steady flow process of an open system is given by

Rate of Energy in = Rate of Energy out

Therefore,

Rate of Energy loss $= \dot{m}_p(h_p - h_g) - [\dot{m}_6(h_7 - h_6) + \dot{m}_a\{(h_a)Air@160^oC - (h_a)Air@25^oC\}]$ (4.21)

Rate of Energy loss =51.12(1764.02–506.91)–[22.38(3461.16–887.03) + 40.75(434.38 – 298.18)]

= 64263.46 – (57609.0 + 5550.15)

= 1104.29 kW

The first law efficiency

$\eta_{I(Heat\ Exchanger)}$ = 1 – rate of Energy loss/rate of Energy in

= 1 –rate of energy loss/$\dot{m}_p(h_p - h_g)$

$\eta_{I(Heat\ Exchanger)}$ =1–1104.29/51.12(1764.02 – 506.91)

=98.20%

Heat exchanger Exergy analysis

ψ: specific exergy flow in kJ/kg

$\psi = (h - h_o) - T_o(s - s_o)$

$= (h - T_o s) - (h_o - T_o s_o)$

It can be noted that the exergy loss due to the heat loss from the heat exchanger (at ambient temperature) is zero.

$\dot{X}_{destruction} = \dot{m}_p\psi_p + \dot{m}_6\psi_6 + (\dot{m}_a\psi_a)Air@25^oC - \dot{m}_7\psi_7 - (\dot{m}_a\psi_a)Air@160^oC - \dot{m}_g\psi_g$

$= \dot{m}_p[(h_p - T_os_p) - (h_g - T_os_g)] - [\dot{m}_6\{(h_7 - T_os_7) - (h_6 - T_os_6)\} + \dot{m}_a\{(h_a - T_os_a)@160^oC - (h_a - T_os_a)@25^oC$

$\dot{X}_{destruction} = 51.12[(1764.02 - 298 \times 8.97) - (506.91 - 298 \times 7.5)] - [22.38\{(3461.16 - 298 \times 6.25) - (887.00 - 298 \times 2.39)\} + 40.75\{(434.10 - 298 \times 2.07) - (298.18 - 298 \times 1.695)\}]$

$= 41869.81 - [31865.76 + 984.92]$

$= 9019.12$ kW

The rate of exergy loss calculated above does not take into account the exergy loss due to the exergy content of flue gases leaving chimney. The exergy content of flue gas is equal to $\dot{m}_g\psi_g$. The exergy of flue gas is also a loss of exergy from the boiler system because this exergy is not utilized anywhere in the plant.

Second law efficiency or exergetic efficiency

$\eta_{II(Heat\ Exchanger)} = 1 -$ Rate of Exergy destruction/ Rate of Exergy in

$= 1 - \dot{X}_{destruction}/\dot{m}_p\ (\psi_p - \psi_g)$

$= 1 - \dot{X}_{destruction}/\dot{m}_p\ [(h_p - T_os_p) - (h_g - T_os_g)]$ (4.24)

$\eta_{II(Heat\ Exchanger)} = 1 - 9019.12/51.12\ [(1764.02 - 298 \times 8.97) - (506.91 - 298 \times 7.5)]$

$= 1 - 9019.12/41869.81$

$= 78.45\%$

5 RESULTS AND DISCUSSION

In present work energy and exergy analysis have been applied to different components of baggase based 20 MW steam power plant and results are presented in Tables 4 and Figures 3-4.

Table 4Energy and Exergy balance for boiler at ambient temperature T_o = 25˚C (298 K)

Energy/Exergy distribution	Energy in kW	Exergy in kW
Total rate of energy input to the boiler	94374.50	103274.83
Rate of energy used to produce steam	57608.97	31865.76
Rate of energy loss through flue gas at chimney	25913.24	1897.06
Rate of heat loss from combustor	9748.01	60498.81
Rate of heat loss from heat exchanger	1104.29	9019.12

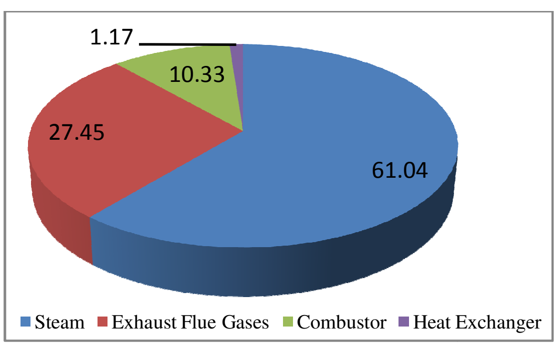

Fig. 3 Energy balance for boiler

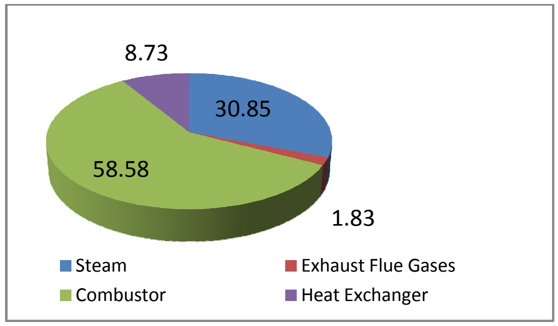

Fig. 4 Exergy balance for boiler

Energy balance has been applied to boiler at ambient temperature of 298 K and results are presented in Table:4 and Fig 3-4. It is noted that maximum thermal energy loss is heat content of flue gas leaving the chimney. Ratio of heat content of flue gas leaving chimney to total energy input is about 27 %. Rate of exergy destruction in different subsystems of boiler are calculated at ambient temperature of 298 K and values are listed in Table 4 and plotted in Fig 5.5. It is noted that maximum rate of exergy destruction of irreversibility is in combustor. Ratio of rate of exergy destruction to rate of exergy input to boiler is around 58% in combustor.

It can be concluded that exergy analysis of power plant is more realistic than its energy analysis. From exergy analysis it is found that boiler and turbine are two main components which offer scope for improvement in a bagasse based steam power plant.

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