International Journal of Research in Advanced Engineering and Technology
www.allengineeringjournal.in
ISSN: 2455-0876
Received: 16-01-2024, Accepted: 01-02-2024, Published: 16-02-2024
Volume 10, Issue 1, 2024, Page No. 1-5

Exergy analysis of a fluidized bed combustor

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Abstract

The ecological concerns relating to greenhouse gases (GHG) have necessitated the quest for the greenisation of energy production and utilisation. Fluidised bed combustion is a vital technology for greener and cleaner combustion of fossil and biomass fuels because of its capability to technically and economically match conventional energy technologies. It offers many superior features, especially regarding emissions and fuel flexibility, making it a suitable technology for different physical and chemical processes. This study presents the exergy analysis based on the second law of thermodynamics for an experimental fluidised bed combustor (FBC) rig. The system comprises two zones: the bed and the freeboard. The exergy analyses were carried out for the two zones, considering the system utilising groundnut shell (GS) as the biomass fuel. The chemical exergy from the fuel was obtained as 1997.27 kJ/kg with a heat transfer rate of 5410.50 kW. Between the two zones, the variance in the exergy storage rates, exergy destruction and entropy generation were 11%, 29% and 29%, respectively. The results also indicated that the highest amount of exergy destruction occurred in the bed region of the FBC system, with 695.84 kW, compared to the freeboard region, with 502.43 kW. The higher exergy destruction in the bed results in the most significant exergy losses over the freeboard since the bed constitutes the heart of the combustor. The higher exergy in the bed is attributable to the combustion (chemical reaction), heat transfer across significant temperature differences and thermal losses in the flow paths.

Keywords: Combustion, exergy destruction, fluidised bed, freeboard and thermodynamic

Introduction

Rapid development, coupled with the world's population and economic expansion, has resulted in a significant rise in energy demand [1]**.** Approximately 85% of global energy consumed is obtained from non-renewable resources, specifically coal, natural gas and oil, contributing to climate change concerns, economic issues and political crises. These resources are finite, and their reserves worldwide are depleting, coupled with increasing prices [2]. The ecological concerns relating to greenhouse gases (GHG) have necessitated the quest for the greenisation of energy production and utilisation.

The Fluidised bed combustion is a vital technology for greener and cleaner combustion of fossil fuels and biomass fuels because it has been able to technically and economically match conventional energy technologies, offers many superior features, especially in terms of emissions and fuel flexibility, and is thus a suitable technology for different physical and chemical processes. Coal gasification, roasting of pyrite and zinc sulphite, catalytic cracking of hydrocarbons, catalysed and non-catalysed gas-particle reactions, drying, and mixing processes are just a few instances of reactions and technologies in which the fluidisation process was used [3].

The fluidised bed combustion technology has proven to be the most effective technology for energy conversion from biomass [4]. In general, fluidised beds are used for energy conversion and evaluated as fuels for coal wastes or coals with low combustion efficiency with biomass. These resources can be used by considering efficiency and environmental responsibilities [5]. The fluidised bed combustor has many advantages over conventional combustion systems, including fuel flexibility, low NOx emissions, in situ control of SO2 emissions, excellent heat transfer, high combustion efficiency, and sound system availability. In addition, it is recognized as an early CO2-mitigation technology by cofiring biomass with coal [6].

Several types of biomasses, such as Cedarwood, wood sawdust, olive oil residue, rice husk and straw, pine sawdust, spruce wood pellet, coffee ground, larch wood, grapevine pruning waste, jute stick, sugarcane bagasse, corn cob, peach stone, wheat straw, cotton stem, straw, camphor wood, beech wood, switchgrass, and others can be used as fuel for fluidized bed combustion. Biomass from forests and agriculture is also used for electricity and heat production [5].

The fluidised bed reactors are categorized into bubbling fluidised bed, circulating and conical fluidised bed, thus a second-generation fluidised bed [7].

Exergy analysis is the most common way of evaluating the performance of different processes. Exergy can identify efficiency improvements and reductions in thermodynamic losses and evaluate energy technologies' environmental benefits and economics [8]. Thus, an Exergy analysis is applied to determine a thermal plant's exergy destruction and efficiency [9]. Advanced exergy analysis was performed on a fluidized bed coal combustor (FBCC) and a heat recovery steam generator (HRSG) in a textile plant using operational data to determine the avoidable exergy destruction rates of the FBCC and the HRSG as 2999 kW and 760 kW according to the measurements. Correspondingly, the exergy efficiencies were modified from 44.2% and 46.2% to 53.1% and 48.1%, respectively

[10]. Also, a study of the energy and exergy analysis of a cogeneration power plant producing steam for salt production was performed through a circulation fluidized bed boiler. It revealed that the energy and exergy efficiency of the circulation fluidized bed boiler was found to be 84.65% and 29.43%, respectively, and the exergy destruction of the circulation fluidized bed boiler was calculated as 21789.39 kW with 85.89% of exergy destruction in the plant [5]. The energy and exergy analyses were done for all the components of a fluidized bed steam power plant comprising a fluidized bed coal combustor (FBCC), an economizer (ECO), a heat recovery steam generator (HRSG), a cyclone, fans, pumps, and a chimney indicated that the highest value of irreversibility was noted in the FBCC, with about 93% of the whole system irreversibility tracked by HRSG and ECO with 3% and 1%, respectively [11]. Furthermore, the energy and exergy analyses of a hybrid solar-biomass fluidized bed drying system showed an average value of 47.6% and 49.5% for an average air-drying temperature of 61ºC and 78ºC, respectively, drying the paddy's moisture content from 20% to 14% (wet basis) with a mass flow rate of 0.125 kg/s [12].

Additionally, an exergy analysis of the propane dehydrogenation (PDH) process inside a fluidized bed reactor (FBR) indicated that the weight hourly space velocity (WHSV) had a significant effect on the exergy efficiency of individual gas components and the total exergy efficiency. Thus, an increase in the temperature from 830 K to 890 K increases propane conversion, thereby increasing the total exergy efficiency of product gases from 99.06% to 99.66%. An increase in the WHSV from 0.40 h^{-1} to 1.00 h^{-1} decreases the conversion of propane, thereby decreasing the total exergy efficiency of product gases from 99.38% to 98.88% [13]. Moreover, energy and exergy analyses of the energy conversion process in a 50 MWth thermal power plant, utilising residual forest biomass as fuel and integrating bubbling fluidised bed combustion technology, indicated that the main exergy destruction occurred inside the combustion process results in 92.2% of the total exergy destruction, corresponding to a 35.5 MW loss of work potential. Also, energy and exergy losses are minimal due to the system’s good thermal insulation [14]. In this paper, the exergy analysis of a fluidized bed combustor rig for biomass fuel combustion was performed to determine the exergy storage rate, the exergy destruction and entropy generation of the combustion process. This would aid in the understudy of the thermodynamic principles of exergy efficiency inherent in the system.

The Fluidized Bed Combustor

The fluidized bed combustor (FBC) is thermodynamically examined. The FBC comprises the bed and the freeboard. A vertical mild steel cylindrical bed was packed with approximately 0.06 m of chosen granular material. The compressed air was supplied to the bed through the distributor plate at a pressure of 600 kPa [15]. Above the bed is a secondary air-port connected 0.55 m above the distributor plate through a 0.01252 m diameter pipe to the freeboard region, thereby promoting the mixing of combustible gases and the volatiles liberated from the bed. The secondary air supplied would ensure the complete combustion of these gases, the volatiles and the un-burnt hydrocarbons released into the freeboard zone. An orifice plate was also inserted into the 0.0254 m pipe carrying the primary air supply to the plenum chamber, and the fluidization process was observed through a stainless-steel reflector inclined above the combustor [15].

The FBC could be employed for steam generation for process heat or electricity generation. The FBC could be divided into two regions: the bed region and the freeboard region. The FBC utilises dried groundnut shell (GS) as the solid biomass fuel, and its compounds are enumerated in Table 1.

Table 1: Element Composition (Dry Basis) of the Groundnut Shell

S/No.	Elements	Mass (%)
1.	Moisture	0.55
2.	Ash	3.25
3.	Carbon	46.99
4.	Hydrogen	6.65
5.	Nitrogen	0.56
6.	Sulphur	0.50
7.	Oxygen	41.50

Source: [15]

The biomass fuel was fed into the combustor through a feed-hopper at feed rates of 0.1, 0.2, 0.3, 0.4 and 0.5kg/s for batch combustion. The hopper was fitted with a vibrator to ensure fuel agitation while entering the combustor from the top of the FBC. The graphic diagram of the investigated FBC is symbolised in Figure 1.

The assumptions made for ease of analysis are:

1. a steady-state fluidised bed system,
2. the ideal gas theories are kept in view for air and combustion gas,
3. the exergy of the ash is not considered since it is assumed to be negligible and
4. the variations in the kinetic and potential energy are ignored.

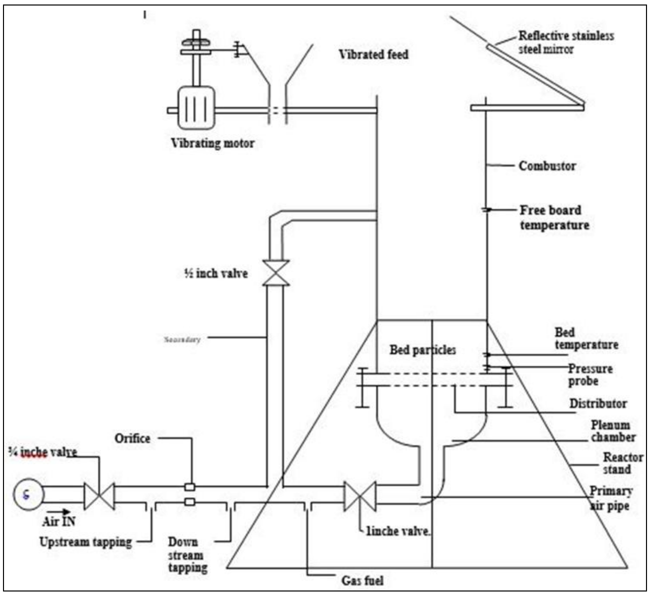

Fig 1: The schematic diagram of the fluidized bed combustor

Methods and Analysis

This study aims to conduct an exergy analysis to comprehend and demonstrate the efficiency of the FBC mechanism. Exergy balance equations generate the principle of thermodynamic relationship, expounding the thermodynamic efficiency of the FBC through the exergy efficiencies based on the second law of thermodynamics.

The thermodynamic tables were used to obtain the properties of air and combustion gases. The ambient conditions for temperature and pressure surrounding the FBC are given as T_0 = 25ºC and P_0 = 101.3 kPa. The constant parameters used for the exergy analysis of the combustor on the dry fuel basis are indicated in Table 2. The specific heat capacity of the fuel was obtained based on its moisture content.

Table 2: Parameters of the fuel (GS) in dry basis

Parameter	Symbol/Unit	Value	Source
Specific heat capacity	c_p (kJ/kg.K)	2.00275	[16]
Higher heating value	HHV (kJ/kg)	18035	[15]
Ambient temperature	T_0 (K)	298	[11]
Ambient pressure	P_0 (kPa)	101.3	[11]

1. Exergy Balance

The exergy indicates the potential work capacity of the system. Exergy is destroyed while it is not preserved as energy. Exergy destruction is expressed as irreversibility, which refers to the system's performance. The exergy is described as the maximum amount of work that a system may generate [11]. The exergy balance for the storage term of a control volume is expressed as [17]:

Rate of Exergy Storage = Transfer by heat +Transfer by shaft(or boundary) work + Transfer by flow-Exergy destruction

This could be expressed in Equation (2) as:

$$\frac{d\phi}{dt} = \sum\left(1 - \frac{T_0}{T}\right)\dot{Q}_{cv} - \dot{W}_{cv} + P_0\frac{dV}{dt} + \sum \dot{m}_i\psi_i - \sum \dot{m}_e\psi_e - T_0\dot{S}_{gen}$$

Since the fluidized bed combustor is applied to combust the biomass fuel (groundnut shell) with no generation of steam involved, the transfer by shaft (or boundary) work and the transfer by flow in Equation (1) can be neglected. Thus, Equation (2) is reduced to Equation (3).

$$\frac{d\phi}{dt} = \sum\left(1 - \frac{T_0}{T}\right)\dot{Q}_{cv} - T_0\dot{S}_{gen}$$

The determination of the heat transfer rate $\dot{Q}_{cv}$ of the control volume can be achieved from the higher heating value (HHV) of the fuel using Equation (4)

$$\dot{Q}_{cv} = HHV \times m_{f(actual)}$$

Where, $m_{f(actual)}$ signifies the actual mass of the fuel used.

The exergy analysis of the fluidised bed combustor is carried out by analysing the exergy occurring in the bed and freeboard regions. Furthermore, this study computes the exergy of destruction (ex_{Des}) in the FBC owing to irreversibility. The physical exergy of the biomass fuel is ignored due to its minor effect, while the chemical exergy of the dry biomass fuel (groundnut shell) used in the FBC is computed by Equation (5) [8].

$$ex^{Ch}_{Biomass} = 1812.5 + 295.606C + 587.354H + 17.506O + 17.735N + 95.615S - 31.8A \text{ (kJ/kg)}$$

Where, C, H, O, N, S, and A are the proportions of carbon, hydrogen, oxygen, nitrogen, sulphur and ash present in the fuel.

The system's performance is stated with Entropy generation (S_{gen}), described as the ratio of the exergy destruction to the ambient temperature. The entropy generation is used to compute the exergy destruction with the help of Equation (6):

$$ex_{Des} = T_0\dot{S}_{gen}$$

The fluidized bed combustor's parts for analysis are schematically demonstrated in Figure 2.

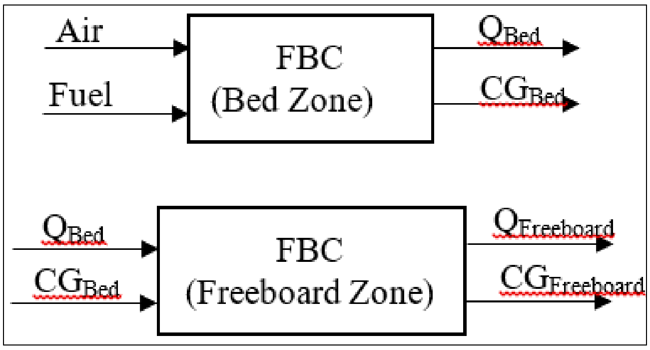

Fig 2: Schematic illustration of the zones of the fluidized bed combustor

Applying the second law of thermodynamics to the fluidized bed combustor yields the exergy balance equations at the bed and freeboard zones as equations (7) and (8), respectively.

$$\dot{m}_{air}ex_{air} + \dot{m}_{fuel}ex_{fuel} = \dot{m}_{CG(bed)}ex_{CG(bed)} + \dot{Q}_{loss(bed)}\left(1 - \frac{T_0}{T_s}\right) + \dot{ex}_{Des}$$

And

$$\dot{m}_{CG(bed)}ex_{CG(bed)} + \dot{Q}_{loss(bed)}\left(1 - \frac{T_0}{T_s}\right) = \dot{m}_{CG(fbd)}ex_{CG(fbd)} + \dot{Q}_{loss(fbd)}\left(1 - \frac{T_0}{T_s}\right) + \dot{ex}_{Des}$$

Results and Discussion

The thermodynamic analysis is achieved by utilizing the second law of thermodynamics to compute the effectiveness of the combustion process. Furthermore, the rate of exergy storage and exergy destruction in the bed and freeboard zones at various fuel feed rates was observed. The entropy generation is computed due to the direct relation with system performance. The outcomes of exergy calculations for the FBC are given in Tables 3 and 4.

Table 3: Computed exergy values at the dead state conditions in the bed zone

Feed rate (kg/s)	T_{bed}(K)	$d\varphi/dt_{(bed)}$(kW)	$ex_{Des(bed)}$(kW)	$S_{gen(bed)}$(kJ/kg.K)
0.10	1151.00	1106.05	230.52	0.7735
0.20	1150.00	2211.68	460.63	1.5457
0.30	1157.00	3321.80	695.15	2.3327

0.40	1155.00	4427.46	925.27	3.1049
0.50	1166.00	5545.25	1167.60	3.9181
Mean value		3322.45	695.84	2.3350

Table 4: Computed exergy values at the dead state conditions in the freeboard zone

Feed rate (kg/s)	T_{fbd}(K)	$d\varphi/dt_{(fbd)}$(kW)	$ex_{Des(fbd)}$(kW)	$S_{gen(fbd)}$(kJ/kg.K)
0.1	770.69	951.80	154.35	0.5180
0.2	783.44	1921.18	313.81	1.0530
0.3	835.94	2979.48	502.25	1.6854
0.4	856.75	4018.44	686.34	2.3032
0.5	854.25	5016.37	855.42	2.8706
Mean value		2977.45	502.4	1.6860

Based on the thermodynamic analysis, the exergy storage, exergy destruction and entropy generation rates of two zones of FBC for each fuel feed rate are displayed in Figures 3 - 5, respectively. The energy storage rates, the exergy destruction and the entropy generation, increased with increasing feed rates in the two zones. However, the combustion process showed that an increase in the fuel feed rate increased the exergy storage rates, with about an 11% variance in the bed over the freeboard zones.

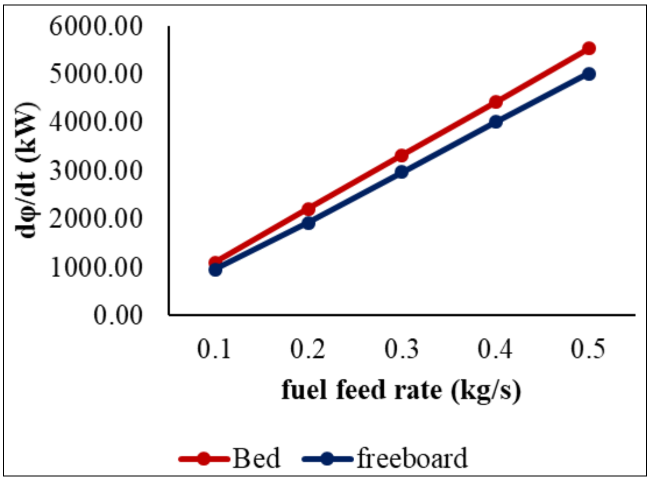

Fig 3: Exergy storage rates in the bed and freeboard zones

Furthermore, an increase in the fuel feed rate yielded an increase in the exergy destruction with about 29% variance in the bed over the freeboard zone.

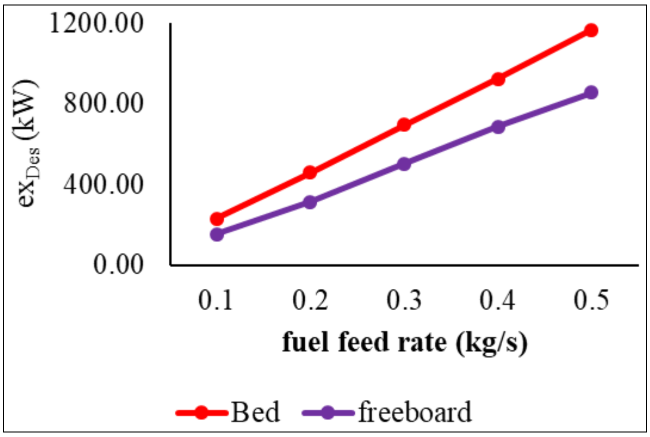

Fig 4: Exergy destruction rates in the bed and freeboard zones

Additionally, the entropy generation is calculated to indicate the performance of the combustor. The entropy generation of the FBC increased with increasing fuel feed rates, with about a 29% variance in the bed over the freeboard zone.

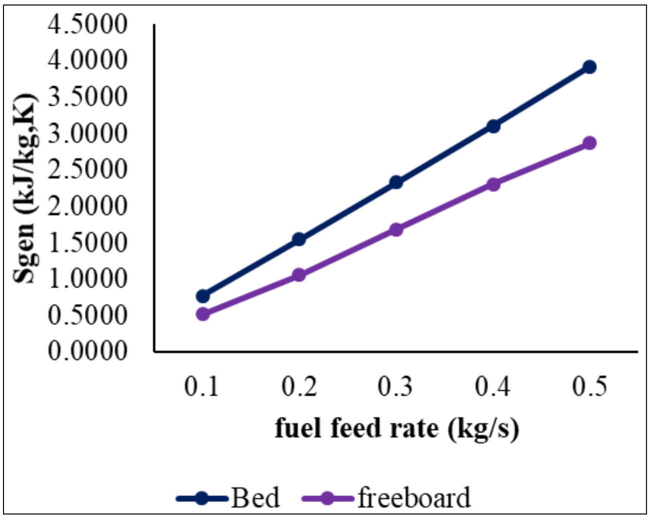

Fig 5: Entropy generation rates in the bed and freeboard zones

The chemical exergy of a system characterises the maximum work extractable from the system at the pressure and temperature of the reference environment as it changes to a system with the same composition, as well as pressure and temperature, as the reference environment [9]. Thus, the chemical exergy from the fuel is 1997.27 kW, as computed from Equation (4) and indicated in Table 5. The mean heat transfer rate generated by the fuel in the FBC is 5410.50 kW.

Table 5: Chemical exergy of the biomass fuel (groundnut shell)

Elements	C	H	O	N	S	A	ex_{fuel}^{Ch}(kW)
Value	0.4699	0.0665	0.415	0.0056	0.005	0.0325	1997.27

The exergy analysis of the system indicates that a mean fuel feed rate of 0.30 kg/s yields mean values of the exergy storage rate, exergy destruction and entropy generation as 3322.45 kW, 695.84 kW and 2.3350 kJ/kg.K, respectively, at the bed. Also, mean values of the exergy storage rate, exergy destruction and entropy generation were obtained at the freeboard at 2977.45 kW, 502.43 kW and 1.6860 kJ/kg.K, respectively. The higher exergy destruction in the bed results in the most significant exergy losses over the freeboard since the bed constitutes the heart of the combustor. The higher exergy in the bed is attributable to the combustion (chemical reaction), heat transfer across significant temperature differences and thermal losses in the flow paths [9]. The higher entropy generation in the system resulting from the high FBC temperatures describes the process's irreversibility.

Conclusion

The thermodynamic analysis is investigated based on the second law of thermodynamics for an experimental FBC rig in this study. The results indicated that the highest amount of exergy destruction occurred in the bed region of the FBC system, with 695.84 kW, compared to the freeboard region, with 502.43 kW. The exergy analysis of the system indicated that a mean fuel feed rate of 0.30 kg/s yields mean values of the exergy storage rate, exergy destruction and entropy generation as 3322.45 kW, 695.84 kW and 2.3350 kJ/kg.K, respectively, at the bed. In contrast, mean values of the exergy storage rate, exergy destruction and entropy generation were obtained at the freeboard at 2977.45 kW, 502.43 kW and 1.6860 kJ/kg.K, respectively. The entropy generation results were higher in the bed region than in the freeboard, leading to higher exergy destruction and greater irreversibility. Thus, the fluidised bed combustor's high exergy efficiency is expected for steam and electricity production.

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