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# Exergy Analysis of Boiler Process Powered by Biogas Fuel in Ethanol Production Plant: a Preliminary Analysis

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**Abstract**

This paper investigates a fluidized bed boiler used in an ethanol production plant. The boiler uses biogas fuel produced by the waste system of the distillation unit within this ethanol plant. Using Engineering Equation Solver (EES), a mathematical model is developed by employing the exergy analysis. Before the study was undertaken, initial operating data of the components in the plant was collected. The results show that the boiler system has an overall efficiency of 68.238 %. The exergy efficiency in each component was also calculated. The evaporator and heat exchanger have the lowest efficiency at 45.97% and 28.96%, respectively. The efficiencies of the other components are 61.41% for the pump water pit, 54.42% for the soft water tank and 66.39% for the de-aerator.



Keyword: Boiler; Exergy; Thermodynamic; ethanol; EES

## 1. Introduction

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Fossil fuels such as oil, natural gas and coal are limited and will be depleted in the near future. Researchers predict that crude oil reserves will be exhausted by the end of the 21st century. It is also expected that coal and natural gas reserves will be depleted in about 70 and 200 years, respectively [1]. The aforementioned fuels are not only getting scarce, but their use has been proven to have grave environmental consequences. Combustion of fossil fuels releases pollutants such as $CO_2$ and $CH_4$, which are now known to be major contributors to the global warming problem. This is evident in melting ice caps as well as higher tides and sea levels [2]. If left unchecked, these events are expected to eventually cause heavy flooding in low-lying cities, shores and islands. Fossil fuel prices are also unstable and it is expected that prices will rise sharply in the future. Although oil prices dropped considerably in 2015 in reaction to world events, it is expected that prices will appreciate as demand for fossil fuel increases. This price increase will mostly be felt by countries which have to rely on fossil fuel imports in order to meet energy demands.

**Nomenclature**

**Symbols**

| | |
|---|---|
| $\dot{m}$ | Mass flow (kg/s) |
| $\dot{Q}$ | heat flow (kJ/s) |
| $\dot{W}$ | Work flow (kJ/s) |
| $\dot{E}X$ | Exergy (kJ/s) |
| h | Enthalpy (kJ/kg) |
| g | gravity (m/s$^2$) |
| Z | elevation (m) |
| ex | specific exergy (kJ/kg) |
| I | irreversitility (kJ/s) |
| T | Temperature (K) |
| s | entropy (kJ/kg.K) |

**Subscript**

| | |
|---|---|
| CV | Control Volume |
| i | Inlet |
| o | Outlet |
| k | Specific stream |
| ke | Kinetik |
| po | Potential |
| ph | Phisical |
| ch | Chemical |
| p | Product |

In commercial plants, including power generation plants and factories in the chemical industry, the problems associated with fossil fuels are well known. This has resulted in a gradual shift away from the use of fossil fuels to renewable energy sources. An ethanol plant in Indonesia have used biogas from the wastes produced by ethanol production as a complementary fuel to reduce energy costs as well as to reduce environmental problems. These plants are considering changing to renewable energy as the availability of residual oil in the domestic market is uncertain and its economic viability in the future is questionable. Once the biogas is used, the performance of whole ethanol production plant needs to be investigated. Exergy analysis by employing the second law of thermodynamics will be used to evaluate the performance of the system powered with biogas. This method has been widely used in studies to measure the improvement of efficiency in geothermal power plants [3]–[6], a coal power generation plant [7], a gas power generation plant [8], a solar tower power generation plant [9], and a nuclear power generation plant, etc. [10]. In ethanol production, exergy analysis is also widely used to improve chemical reactions within the reactor [11]–[13]. In this study, the efficiency of a fluidized bed boiler by utilizing data recorded over the period of one year. The data can be used to devise an optimal procedure to increase boiler performance.

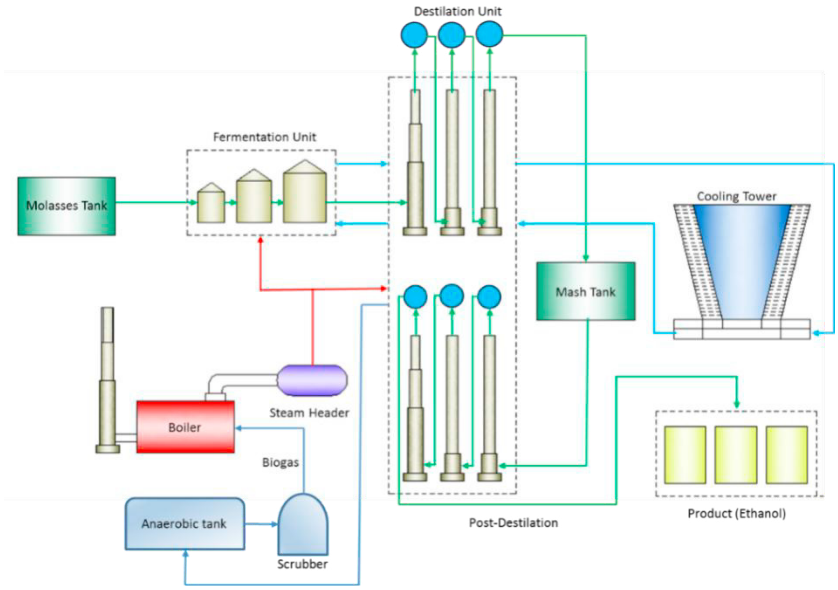


Figure 1. Ethanol production processes including the boiler and biogas system.

## 2. System description of ethanol production system

In the ethanol production system, the main processes consist of ethanol unit, biogas fuel production and the boiler system. The biogas fuel system produces a biogas, mainly $CH_4$. The boiler produces steam and sends it to the steam header. Steam is then sent to the ethanol unit. In this unit, this ethanol system received pressurized steam at around 7 bar from the steam header. The waste for producing biogas comes from the distillation unit, as shown in Fig 1. The gas produced by the anaerobic tank is sucked by a blower to the scrubber. It is then compressed to filter impurities carried by methane gas. The methane is sent to fuel control before being fed to the combustion chamber in a boiler.

## 3. Boiler process details

To provide heat for the ethanol production processes, a boiler is used to create a low-pressure steam. The boiler process begins in a water pit, in which water is stored at a temperature of 27 ºC and a pressure of 1.01 bar. The stored water is pumped into a soft water tank 15 meters above the ground, moving at a rate of 3.21 kg/s and a pressure of 4 bars. High levels of calcium and magnesium in hard water can cause scaling, which reduces the efficiency of boiler equipment. Before entering the boiler process cycle at the water pit, the water has been filtered and softened to eliminate these materials.

Table 1. Boiler spesification

| Variable | Specification |
|---|---|
| Capacity | 14 Ton/hr |
| Working pressure of steam | 10-11 Bar |
| Steam Temperature | 350 ºC |
| FW Temperature | 160 ºC |
| The area of heat | 106,158 m$^2$ |
| Fuel | Residue oil/Methane (biogas) |

From the soft water tank, the stored feed water passes into the pre-heater, which uses the blowdown water from the boiler to increase its temperature to 37 ºC. This reduces the irreversibility involved in the boiler system and increases its thermodynamic efficiency. The blowdown water comes from the boiler at 166.7 C, but after being used in the pre-heater, its temperature drops to 96 ºC.

From there, the feed water enters the de-aerator, where non-condensable gases such as oxygen and carbon dioxide that could cause corrosion in system pipes are removed. At the de-aerator outlet, where steam from the boiler is employed at a temperature of 166.7 ºC, the feed water heats up further to about 100.1 ºC. Once it enters the boiler, the feed water is heated until it becomes dry steam with a temperature of 172 ºC. This dry steam is sent into the steam header, where it is eventually used in the ethanol plant for the fermentation and distillation of molasses. Blowdown water from the boiler returns to the de-aerator or pre-heater.

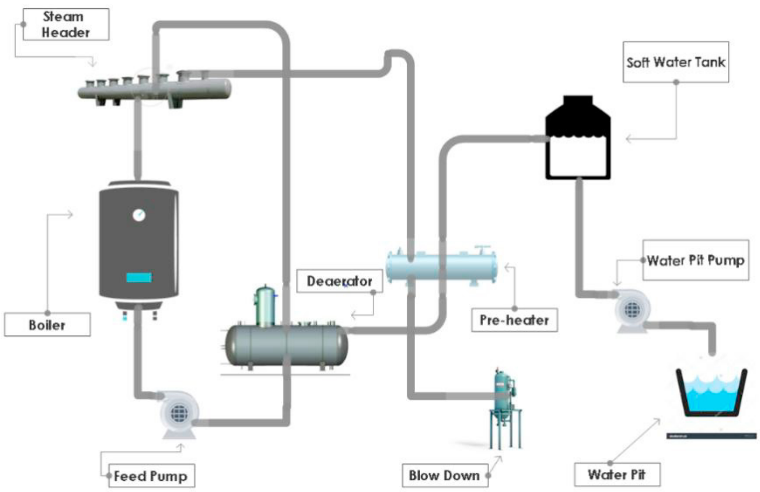


Figure 2. Boiler process in detail

## 4. Method analysis

Exergy analysis is a tool used to evaluate and measure thermal loss in terms of type, quality and quantity. To calculate this method, first and second law thermodynamic method are employed as follows:

$$\sum \dot{m}_{i,\,cv} = \sum \dot{m}_{0,\,cv} \tag{1}$$

where $\dot{m}_{i,\,cv}$ is the mass flow rate entering the control volume and $\dot{m}_{0,\,cv}$ is the mass flow rate flowing out the control volume. Eq.(1) represents the law of mass conservation that the mass that enters a control volume is a system. The total mass flow entering the control volume is equal to the outlet.

The Eq.(1) is then expanded to the Eq.(2) as follows:

$$\dot{Q} - \dot{W} = \sum \dot{m}_0\, h_0 - \sum \dot{m}_i\, h_i \quad (2)$$

Where $\dot{Q}$ is the heat added into the system, $\dot{W}$ is the work producesdand *h* is the enthalpy. Subscript *o* is the outlet and *i* is the inlet.
Eq.(3) is the expansion of the Eq.(2) with kinetic, $\frac{C^2{}_i}{2}$ and potential energy, $gZ_i$ fully considered.

$$\sum \dot{Q} \quad + \sum \dot{m}\left(h_i + \frac{C^2{}_i}{2} + gZ_i\right) = \sum \dot{m}\left(h_0 + \frac{C^2{}_0}{2} + gZ_0\right) + \sum \dot{W} \quad (3)$$

After observing the expression of energy, the exergy equations, as in Eq.(4) to Eq.(10), are further examined.

$$\sum \left(1 + \frac{T_0}{T}\right) Q_k + \sum (\dot{m}_i ex_i) = \sum \psi_w + \sum (\dot{m}_0 ex_0) + \dot{I}_{destroyed} \quad (4)$$

$\dot{I}_{destroyed}$ is the irreversibility, and this is used to determine how much exergy in a component is lost during the process.

$$EX_k = \dot{m}\; ex_k \quad (5)$$

The Exergy rate in specific stream, *k*, is equal to specific exergy in stream *k*, as shown in Eq.(5). Then, Eq.(4) is substituted into Eq.(6).

$$Ex_k = \dot{m}((h_k - h_0) - T_0(s_k - s_0)) \quad (6)$$

Where exergy in specific stream can be written as Eq.(7):

$$ex_k = (h_k - h_0) - T_0(s_k - s_0) \quad (7)$$

Specific exergy can be written as in Eq.(8)

In the system, the total specific exergy is equal to kinetic, potential, phisic and chemical exergy, as shown in Eq. (8). However, here we ignored the kinetic and potential exergy.

$$ex_{total} = ex_{ke} + ex_{po} + ex_{ph} + ex_{ch} \quad (8)$$

Second law efficiency can be calculated as a ratio between fuel and product exergy. Therefore the exergy efficiency can be calculated using Eq.(11) [14].

$$\eta_{II} = \frac{\dot{E}_p}{\dot{E}_i} \quad (9)$$

## 5. Result and Discussion

Second law analysis was carried out, considering a wide range of factors such as enthalpy and entropy, by analysing the exergy of each state as well as the process. Thereafter, the Grassmann diagram was plotted and the efficiency of each piece of equipment was calculated.

### 5.1. Main state parameters

The results of the boiler process are presented in Table 2.

Table 2: Table showing the state parameters when using biogas

| State | Process | P | T | h | s | $\dot{m}_g$ | $\dot{E}_{Tot}$ |
|---|---|---|---|---|---|---|---|
| | | Bar | °C | (KJ/Kg) | (KJ/Kg.K) | (Kg/s) | KW |
| 1 | Inlet of water pit pump | 1 | 27 | 113.29 | 0.3952 | 6.9 | 0.36 |
| 2 | Inlet of soft water tank | 4 | 27.01 | 113.59 | 0.3952 | 6.9 | 4.52 |
| 3 | Inlet of heat exchanger | 4 | 27 | 113.57 | 0.3961 | 6.9 | 2.46 |
| 4 | Inlet of feed water pump 1 | 9 | 46.83 | 196.87 | 0.6622 | 6.9 | 49.8 |
| 5 | Inlet of de-aerator | 9 | 46.83 | 196.87 | 0.6622 | 6.9 | 55 |
| 6 | Inlet of feed water pump 2 | 17 | 94.88 | 398.77 | 1.2477 | 11.31 | 701.25 |
| 7 | Inlet of evaporator | 7.73 | 95.05 | 398.77 | 1.2503 | 11.31 | 700.04 |
| 8 | Inlet of boiler | 7.73 | 168.96 | 714.65 | 2.0317 | 11.31 | 2566.62 |
| 9 | Inlet of de-aerator | 9 | 168.94 | 714.65 | 2.0314 | 4.41 | 1001.2 |
| 10 | Inlet of heat exchanger | 5 | 168.96 | 2787.85 | 6.9128 | 0.247 | 208.8 |
| 11 | Outlet of heat exchanger | 5 | 110 | 461.42 | 1.4184 | 0.247 | 11.4 |
| 12 | Inlet of steam header | 7.73 | 168.96 | 714.65 | 2.0317 | 6.653 | 1509.78 |
| 13 | Outlet of steam header | 7.73 | 168.96 | 714.65 | 2.0317 | 6.653 | 1509.78 |

Most noticeably, the total exergy at stage 8, where liquid turns into steam, is reduced to 2566.62 kW.

### 5.2. Grassmann diagram

Grassmann diagrams are used to represent the exergy flow. Before Grassmann diagrams can be drawn, the irreversibility of each component must be considered and factored in. Grassmann diagram can be used as effective tools to determine where there is a heat loss in a system.

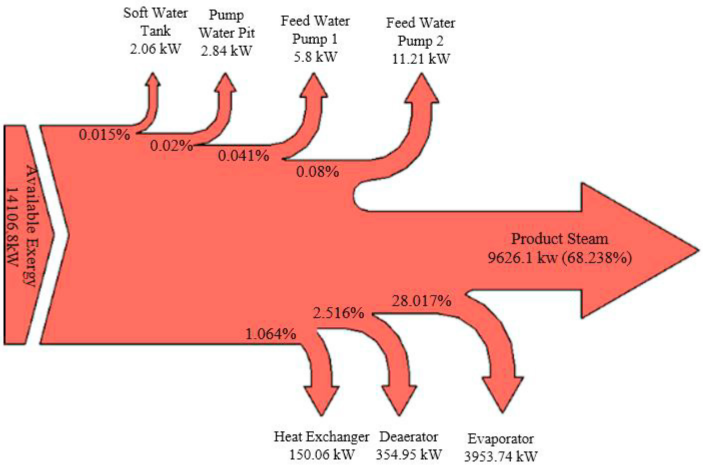


Figure 3. Grassmann diagram for the boiler

Fig. 3 shows the exergy flow during the boiler process. The available exergy is 14106.8 kW. Exergy entering the boiler used by 68.24% (9626.1 kW) and loss is about 4480.7 kW (31.76%). Irreversibility from the component is as follows: from the soft water tank it is 2,06 kW (0.015%), from the pit water pump it is 2.84 kW (0.02%), from feed water pump 1 it is 5.8 kW (0.041%), from feed water pump 2 it is 11.21 kW (0.08%), from the heat exchangers it is 150.06 kW (1.064%), from the de-aerator it is 354.95 kW (2.516%), and the highest loss occurred in the evaporator (3953.74 kW, 28.01%).

### 5.3. Component Efficiency

Fig. 4 shows the efficiency of the components such as the feed water pump, pit water pump and steam header. The evaporator and heat exchanger have the lowest efficiency.

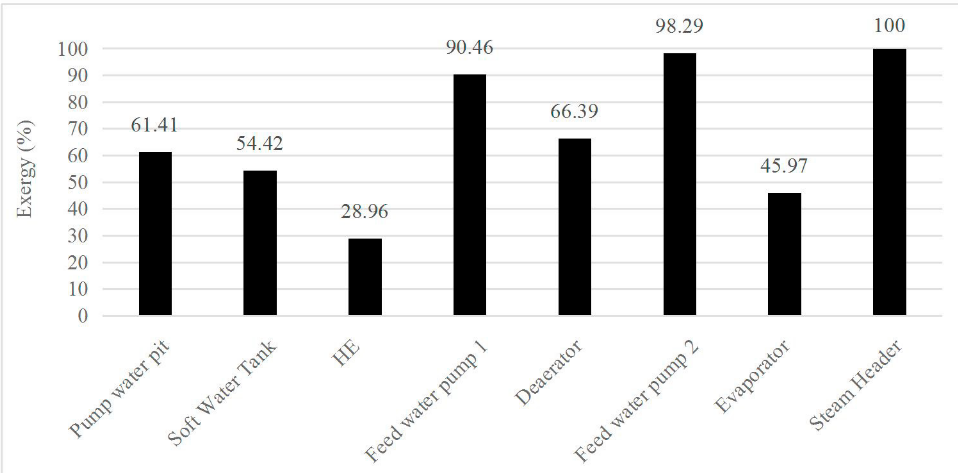


Figure 4. Exergy efficiency for the boiler components

## 6. Conclusion

With the uncertainty surrounding the future of fossil fuels, both in terms of price and availability, coupled with their known detrimental effects on the environment, industries of all types are increasingly searching for sustainable alternatives. One such alternative which shows huge potential is biogas. Exergy analysis is a methodology often used to determine the efficiency of processes of the plants. The available exergy from biogass fuel is assumed as 14106.8 kW. Exergy entering the boiler used by 68.24% (9626.1 kW) and loss is about 4480.7 kW (31.76%). In the component efficiency, the evaporator and heat exchanger have the lowest efficiency. As this research is preliminary only, further detailed research will be required in the future by using biogas fuel as a chemical exergy. However, this can only be done if the chemical fuel data is available. Therefore, the boiler system could be improved.

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