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Performance evaluation and optimization of fluidized bed boiler in ethanol plant using irreversibility analysis

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A R T I C L E I N F O

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Ethanol
Performance assessment
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A B S T R A C T

This research aims to evaluate the performance of a fluidized bed boiler in an ethanol production plant through exergy and irreversibility analysis. The study also includes the optimization of the pre-heater and the deaerator in order to improve the system efficiency. Operational data from the ethanol production plant was collected between 2015 and early 2016. The total exergy derived from the fuel was determined to be 7783 kJ/s, while the exergy efficiency of the system was found to be 26.19%, with 2214 kJ/s used in steam production, while 71.55% was lost to component irreversibility and waste heat from the pre-heater. The exergy efficiencies of individual components of the system such as the boiler, deaerator, and pre-heater were found to be 25.82%, 40.13%, and 2.617%, respectively, with the pre-heater having the lowest efficiency. Thus, the pre-heater has the highest potential to significantly improve the efficiency of the boiler system. The optimization of the pre-heater shows that a rise in temperature in the outlet of the pre-heater positively affects the exergy efficiency of the deaerator.

1. Introduction

The rapid depletion of fossil fuel resources coupled with unstable prices and environmental concerns have accelerated concerns in the area of energy efficiency. A study conducted by McGlade to estimate the total volume of tight oil recoverable worldwide suggests that between 150 million to 508 million barrels exist [1]. Similar estimates for coal and gas resources, such as coal bed methane, tight gas, and shale gas are put at 39, 54, and 193 TCM, respectively [2]. It is evident from these values that all non-renewable energy sources will be depleted in the near future. Despite oil prices plummeting to below $30/barrel in 2015, crude oil resources will still be depleted in the future. In order to ensure energy security, countries are currently engaged in activities geared at improving fossil fuel management. In a study by Ediger et al., 2007, a sustainability index comprising several factors such reserve-production, production-consumption, and carbon emission ratio was designed using data from 62 countries [3]. This indexing allows for better planning regarding fossil fuel consumption relative to its reserves.

In the power generation and commercial sectors, there are various methods employed in order to reduce the consumption of fossil fuels. The methods include the reduction of fossil fuel consumption as well as the replacement of fossil fuels by renewable energy

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Nomenclature

Symbols

$\dot{m}$	Mass flow (kg/s)
$\dot{Q}$	heat flow (kJ/s)
$\dot{W}$	Work flow (kJ/s)
$\dot{EX}$	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)
TCM	Trillion Cubic Metres
RP	Reserves-production
PC	Production-consumption
Mtoe	Tonne of oil equivalent
FDF	Force Draft Fan
IDF	Induced Draft Fan

Subscript

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

sources. This is to ensure that fossil fuels remain available for a longer period of time. It is, however, at an economic disincentive to the commercial sector, as it usually translates into lower profit; hence, it is rarely implemented. In the power generation sector, the implementation of this method also usually translates into slowed economic growth and, as such, is not commonly implemented. For instance, China's energy consumption increased drastically from 1793 Mtoe in 2005 to 3014 Mtoe in 2015. This puts China as the highest consumer, having overtaken the United States, which has a total energy consumption of 2280 MToe [4]. Most of the fossil resources used are coal and petroleum [5].

Therefore, the optimization of the plant seems to provide the highest opportunity for energy management. It does not require a huge investment or translate into the reduction of energy consumption in the plant. Rather, it can minimize energy waste and reduce associated emissions. Energy optimization in a plant can also improve labor productivity since the same amount of energy is used to produce better products in terms of both quantity and quality. Exergy analysis is an optimization method widely used in several studies and instances such as the improvement of geothermal power plant efficiency [1–4], coal power generation plant [5], gas power generation plant [6], Solar tower power generation plant [7], nuclear power generation plant, etc. [8]. In ethanol production, it is also widely used in improving chemical reactions within the reactor [9–14]. Dadak et al. conducted the exergy performance assessment of ethanol and acetate formation in a batch bioreactor using clostridium ljungdahlii under various syngas pressures of between 0.8 and 1.8 atm. The result showed that the lowest overall normalized exergy destruction was found to be 49.96 kJ/kJ [9]. Also, Aghbashlo et al. conducted the exergy analysis of an ethanol production process using a continuous stirred tank bioreactor [10,12]. Furthermore, Ojeda et al. carried out studies on the enzymatic hydrolysis reaction of lignocellulosic biomass for the

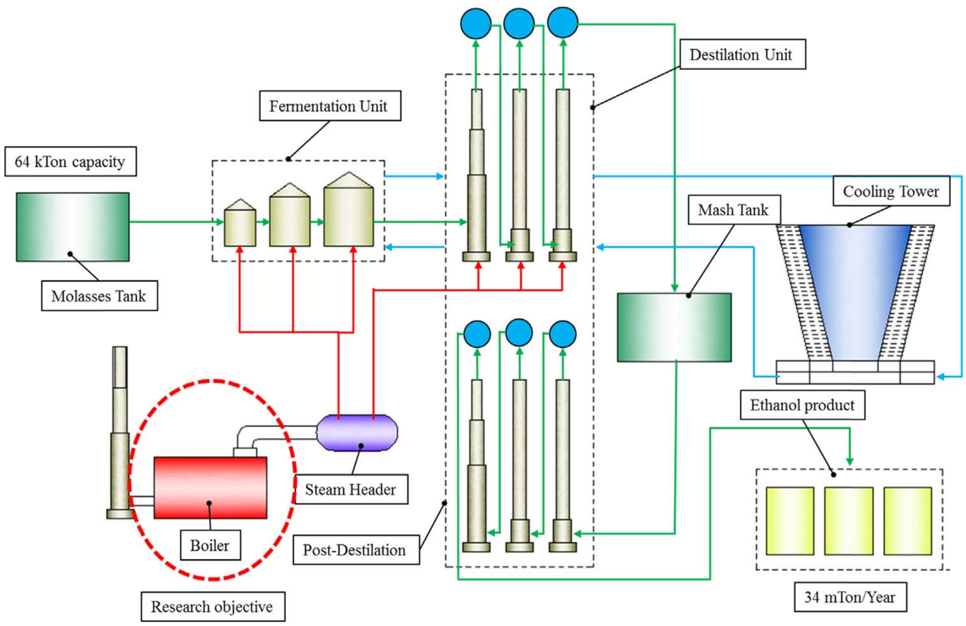

Fig. 1. Process layout of the ethanol production plant.

production of second generation bioethanol [14]. Other ways of producing ethanol include gasification of woody feedstock. This process involves the steam blown indirect biomass gasification of woody feedstock. The possibility of integrating ethanol production and power generation is being investigated by several researchers with ideas such as a poly-generation plant that produces power, heat, and lignocellulosic ethanol or a combined ethanol and biogas plant [15,16].

Most of the research within ethanol production is focused on chemical reaction; however, this research is focused on the exergy analysis of the steam production needed to support the chemical reactions. This steam is produced in the boiler, which uses coal as fuel. Therefore, optimizing the performance of the fluidized bed boiler to provide pressured steam for the distillation and fermentation unit would save more coal resources. This exergy analysis is also capable of detecting disorders in the components within the boiler, such as pre-heater, deaerator, boiler, and pump. To carry out this analysis, the Engineering Equation Solver (EES) is used to solve the mathematical equations that initially developed. Daily operating data for a year was obtained and used in the course of this analysis.

2. System description

2.1. Ethanol plant description

To produce ethanol, pressurized steam is required to increase the fermentation and distillation temperature. The quality and quantity of this steam is maintained for this unit. The plant in this study has an ethanol production capacity of 34 million kg/year, and the process starts from the extraction of molasses from sugar mills before it is sent it to the molasses tank, which has a capacity of 64 kTon. Initially the molasses enters the fermentation unit, which converts it into sucrose by the action of yeast as shown in Fig. 1. The fermentation unit consists of three main parts: seed fermenter, pre-fermenter, and main fermenter. In these three fermentation units, yeast is added, and it is then left for about 12–16 h. This is done in order to increase the volume of the molasses. The mash produced from the fermentation unit is then piped to the distillation unit. In this unit, there are several towers: mash distillation, hydro selection column, and rectifying column. The mash coming into distillation towers will first be vaporized and then condensed to convert it into the liquid ethanol. The liquid ethanol then enters into the hydro selection column where the ethanol is separated from the impurities. This separation process takes places in the rectifying column.

The heater in the distillation unit uses steam coming from the boiler. Pure ethanol produced from the alcohol distillation unit will subsequently be temporarily stored in the tank before being transported to the market. Our exergy analysis covers only the boiler section, which provides steam to the ethanol plant. This is briefly described in the next section.

2.2. Boiler description

In this study, we analyze a bubbling fluidized boiler using coal fuel. This boiler produces steam for the production process. This coal is the bituminous type, having diameters in the range of 0.1–2.5 mm, with caloric values between 4800–6000 kcal/kg. All these properties are conveniently presented in Table 1.

The boiler consists of a combustion chamber featuring sand embedded fluidization. This is equipped with a water tube located at the wall of the boiler and a fire tube at the top of the combustion chamber. The water tube is supported by the concrete membrane wall. This boiler is capable of producing steam at 15,000 kg/h and can hold feed water up to a maximum capacity of 20,900 l. The temperature of the combustion chamber is estimated to be between 800 °C and 1000 °C, while the produced steam has an average temperature of 172 °C.

In the heat generation process, coal is sent into the hopper. It is then transferred to the furnace through the coal feeder screw. However, the coal is passed through the fuel chamber before going into the furnace. At the start of the process, the coal and silica mixture is not introduced into the furnace until the furnace reaches a temperature of 600 °C. To achieve this temperature, charcoal is burnt in the furnace until the desired temperature of 600 °C is reached. During the combustion process, the Force Draft Fan (FDF) takes in air and ejects it through nozzles located under the bed. Normally, the combustion of the coal leaves ash from the Induced Fan Draft (IFD) and is removed through the ash screws.

Table 1
Fuel and boiler specification.

Fuel type	: Bituminous Coal
Origin	: Kalimantan, Indonesia
Grain size	: 0.1 s.d. 2.5 mm
Coal ultimate analysis	: 85% Carbon (C), 6% Hydrogen (H_2), 8% Sulfur (S), 1% Oxygen (O_2)
Coal Caloric value	: 4800–6000 kcal/kg
Quality	: Medium
Burning point	: 600–700 °C
Combustion temperature	: 800–1000 °C: 6–10 bar: 16 bar: 15,000 kg/h
Work pressure	
Maximum pressure	
Capacity	

2.3. Process cycle

Fig. 2 shows the diagram of the boiler process cycle starting from the water pit. The water from the pit is at a temperature of 27.01 °C and a pressure of 1.01 bar. The water was first filtered and softened to eliminate minerals like calcium and magnesium. This soft water is then piped from the water pit pump to the soft water tank. The water pump is capable of pumping 3.21 kg/s at a pressure of 4 bars. It is then stored in the soft water tank 15 m above ground.

The stored feed water is then passed into the pre-water heater. The temperature is increased to 37 °C. The pre-heater uses the blow down water from the boiler, which has a temperature of 166.7 °C. After being used in the pre-heater, the blow down water drops to 96 °C. The feed water is then passed into the deaerator. Non-condensable gases are then removed, with the temperature of the feed water rising to about 100.1 °C at the deaerator outlet, since the deaerator employs the steam from the boiler at a temperature of 166.7 °C. The feed water is then pumped into the boiler until it reaches a pressure of 17 bars. It is then heated to produce dry steam with a temperature of 172 °C. The produced dry steam is then sent into the steam header, where it is eventually used in the plant for the fermentation and distillation of molasses in the ethanol process. In this situation, there is an inefficiency in the system operation, as the pump has a high pressure of 17 bar while the boiler operating pressure is only 7.3 bar. This large pressure drop should be analyzed in the future.

3. Thermodynamic method

Exergy analysis is a technique useful in measuring the thermal loss in terms of type, quality, and quantity. Moreover, it helps in identifying the location and source of the thermal loss [17]. Here, exergy analysis is used to evaluate the performance of the components directly related to the transfer of thermal energy, such as boilers, heat exchanger, and pump. To calculate this method, the first and second law thermodynamic methods 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 which states that the mass that enters a control volume is a system. The total mass flow entering the control volume is equal to the outlet.

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

$$\dot{Q} - \dot{W} = \sum \dot{m}_0 h_0 - \sum \dot{m}_i h_i \tag{2}$$

Where $\dot{Q}$ is the heat added into the system, $\dot{W}$ is the work produced and h is the enthalpy. Subscript *o* is the outlet and *i* is the inlet.

Eq. (3) is the expansion of Eq. (2) with kinetic, $\frac{C^2i}{2}$ and potential energy, gZ_i fully considered.

$$\sum \dot{Q} + \sum \dot{m}\left(h_i + \frac{C^2i}{2} + gZ_i\right) = \sum \dot{m}\left(h_0 + \frac{C^20}{2} + gZ_0\right) + \sum \dot{W} \tag{3}$$

After observing the expression of energy, the exergy equations, as in Eqs. (4) to (9), are further examined.

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

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

$$EX_k = \dot{m}ex_k \tag{5}$$

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

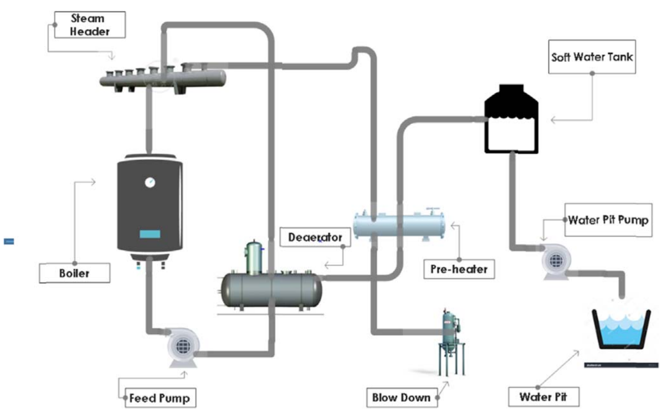

Fig. 2. Boiler process in detail.

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, physic, 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. (9) [18].

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

4. Operating plant data (ini data coal)

For the purposes of this study, operating data of the boiler was carefully gathered between the year 2015 and 2016. This operating data comprises data specific to the study, such as vapor pressure, feed water, flue gas, and combustion chamber temperature, and is quite sensitive to changes in pressure, water level, and amount of fuel entering the combustion chamber. This data is used in assessment of the performance of the boiler. To simplify the analysis, hourly data is transformed into monthly data by taking an average of the hourly data.

Monthly data collected for the period of 12 months is presented in Fig. 3. The average annual consumption of coal amounts to 1484.99 kg/h. The highest consumption of coal occurred in September 2015, amounting to 1864.99 kg/h, while the lowest occurred in May 2015 with a consumption of 1130.15 kg/h. Annual steam production was averaged at 10,305.76 kg/h, with the highest and lowest volumes of steam amounting to 13,077.73 kg/h and 7810.28 kg/h, respectively, produced in August 2015 and May 2015, respectively. The boiler is difficult to determine from information on fuel consumption and steam production, as both factors are highly dependent on the company's needs. The decision to increase production consequentially increases the required amount of steam, which increases the amount of feed water and coal needed. The reverse also holds true.

5. Result and discussion

5.1. Parameter of the boiler states

To calculate the amount of exergy at each state in the process cycle in Fig. 2, parameters such as mass flow rate, pressure, and temperature for each state should be collected based on actual data from the plant. In the event that some parameters are unavailable, it might be necessary to make certain assumptions in order to carry out relevant calculations. Using data from the property database in the EES, various parameters such as enthalpy and entropy can be determined. Thus, exergy and energy values can be calculated. All these parameters, including energy and exergy values for each state, are presented in Table 2. State 0 shows the reference state of the liquid water, showing that pressure and temperature at this state is 1.01 bar and 27.01 °C, respectively. In state 1, feed water enters the pump. Here, the feed water exergy has a value of 0 since it is in its reference state. State 2 is the outlet of the pump, and the pressure of water increases to 4 bar. Alongside this increase in pressure is a little increase in temperature. At this point, the total amounts of exergy and energy are 0.9632 kJ/s and 1.12 kJ/s, respectively. In state 3, feed water enters the water pit pump. The soft water tank is to store the water. Since there is no thermal or mechanical process involved, it is, therefore, assumed that the amount

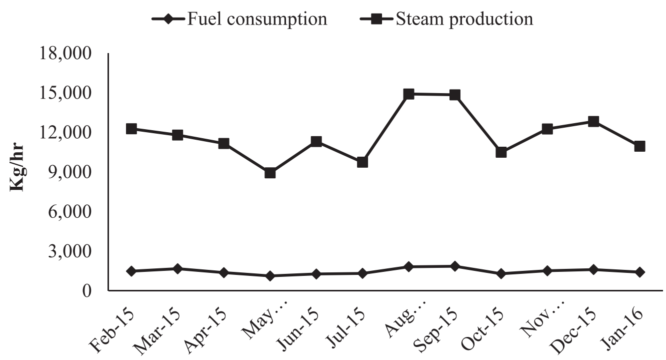

Fig. 3. Consumption of fuel and steam production in monthly average.

Table 2
Parameters for the major stages of a boiler system.

States	$\dot{m}$ (kg/s)	p (bar)	T (°C)	h (kJ/kg)	s (kJ/kg °C)	$\dot{Ex}$ kJ/s	$\dot{En}$ kJ/s
0		1.01	27.01	113.3	0.395		
1	3.21	1.01	27.01	113.3	0.395	0	0
2	3.21	4	27.03	113.6	0.395	0.963	1.12
3	3.21	4	27.03	113.6	0.395	0.963	1.12
4	3.21	4	34.26	143.9	0.4948	2.169	98.24
5	3.633	1.3	107.1	449.2	1.387	139.5	1221
6	3.633	17	107.3	451.1	1.388	145.7	1228
7	3.633	7.3	172	2778	6.723	2784	9681
8	2.889			2778	6.723	2214	7698
9	0.423		166.7	2765	6.694	322.6	1122
10	0.321		166.7	704.8	2.009	34.41	189.9
11	0.321		96	402.2	1.261	9.31	92.74
12	4.601			303.6	5.713	0	0
13	4.601		196	471.7	6.157	159.9	773.3

exergy is constant. After leaving the soft water tank, the feed water enters the pre-heater in state 4. The pre-heater receives heat from blow down water from the boiler. This blow down water is analyzed in state 10. The mass flow of blow down water has been set to be around 10% of total feed water mass flow, and this amounts to 0.321 kg/s. The amount of exergy then increases to 2.169 kJ/s at state 4, which is the outlet of the pre-heater. The temperature also increases from 27.03 to 34.26 °C. The temperature of the blow down water after the pre-heater (state 11) also decreases to 96 °C. All analysis performed so far is based on real plant data.

The heat transfer at the pre-heater is low due to the short length of the heat exchanger. This is a locally manufactured heat exchanger, and, in the future, this heat exchanger should be optimized to increase the amount of heat transferred from the water blow down to feed water. In state 5, the pre-heated feed water enters the deaerator. The deaerator receives heat from the mass flow of steam from the steam header (state 9). Steam mass flow was found to be 0.423 kg/s. The amount of exergy at this location (state 5) after receiving heat then becomes 139.5 kJ/s, with temperature increasing to 107.1 °C. At state 6, which is the outlet of the feed water pump, the feed water, after being pumped to a pressure of 17 bar, has a total exergy of 145.7 kJ/s. State 7 represents the outlet of the boiler. At this state, the feed water changes phase liquid to steam. This increases the exergy to 2214 kJ/s. This significant increase can be attributed to the increase in temperature. State 8, represents the inlet of the steam header, while state 12 represents the inlet of air into the furnace. State 13 represents the flow of flue gas to the environment. The temperature of the flue gas is quite high, owing to the fact that the plant does not utilize this heat.

5.2. Grassmann diagram

The Grassmann diagram, as shown in Fig. 4, is used to ease the measurement and analysis of the rate of exergy destruction otherwise known as irreversibility. In total, exergy amounts to 7783 kJ/s. This amount of available exergy comes from the fuel. However, in our analysis, it is not calculated directly, since there is available data on the temperature and pressure of the boiler. Therefore, the total exergy is calculated based on boiler energy demand. The boiler, however, is only able to utilize 28.45% of the incoming exergy to produce 2214 kJ/s of steam. The remaining 71.55% can be attributed to the pump, preheater, boiler deaerator,

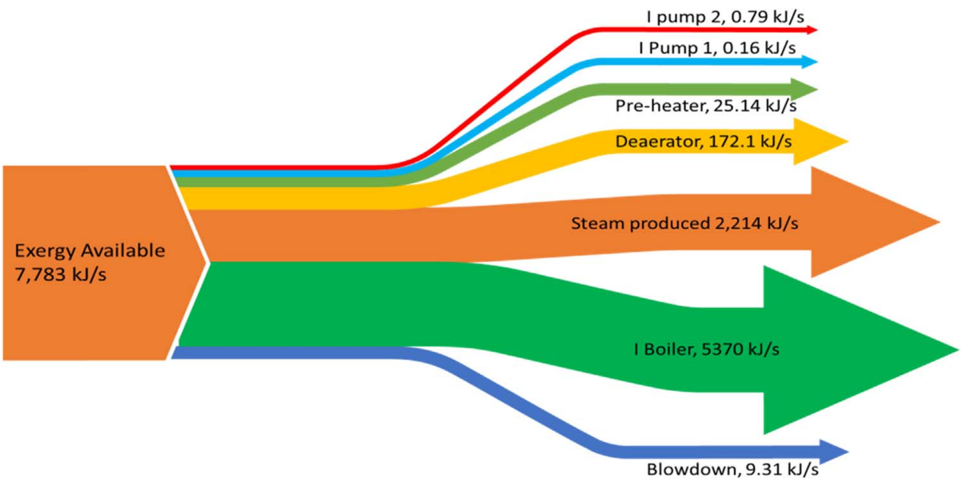

Fig. 4. Grassmann diagram of the boiler system.

and small amounts of waste exit to the environment from the pre-heater outlet.

5.3. Exergy efficiency of individual components

Fig. 5 shows the exergy efficiency of the individual components, such as the water pit pump, soft water pump, pre-heater, deaerator, feed pump, and boiler. The water pit pump is operated to move feed water from the soft water tank while the soft water pump is operated at a pressure of 17-bar pressure to move feed water from the deaerator to the boiler. In this analysis, it is confirmed that the pre-heater has the lowest efficiencies at 6.13% because the total mass flow from blow down water is restricted to 10% of feed water. While the deaerator has an efficiency of 42.97%. This is later discussed in Section 5.5, as these two components will be discussed in detail in regards to the aforementioned reason and their improvement since it influences the overall total efficiency of the boiler system.

5.4. Pre-heater optimization

As described earlier, the pre-heater is one of the components that should be examined in order to optimize the boiler system. The pre-heater utilizes the waste heat of the blow down water from the boiler to raise the temperature of the feed water. The plant in this study has been modified according to the specifications of the local manufacturer. In several plants, it is common to use a flash tank to harness the blow down water. However, in this plant, the blow down water is directly piped to the pre-heater. This is one the reasons why the pre-heater has such a low efficiency, as it uses only very small mass flow from water blow down. The mass flow of blow down water has been set to be around 10% of total feed water mass flow. Other reasons for this low efficiency can be linked to its design, given that the pre-heater is also a small component with short length. In addition, the blow down water flows too fast inside the pre-heater. Technically, to maximize its efficiency, a layer system featuring a longer tube within the heat exchanger should be installed. This would allow the blow down water to stay much longer in the system, hereby increasing the heat transfer. However, this analysis is not focused on heat exchanger design. In this analysis, the pre-heater temperature output is analyzed to improve its efficiency by varying the temperature of the feed water outlet.

Fig. 6 shows the relationship between the temperature of the feed water outlet and the pre-heater efficiency. Using this diagram, the behavior of the temperature of the blow down water at the pre-heater can be explained. If the temperature of the feed water is increased, the exergy efficiency of the pre-heater increases; however, the temperature of the blow down water at the pre-heater outlet will decrease since much more heat is transferred to feed water inside the pre-heater. For example, when the temperature of the feed water to deaerator is increased from 34 °C to 40 °C, the temperature of the pre-heater blow down water outlet decreased from 98.6 °C to 38.75 °C. Therefore, the exergy efficiency of the pre-heater increased from around 6–13.33%. This scenario assumes a constant mass flow of 10% of the blow down water at the feed water inlet of the pre-heater.

The deaerator efficiency is affected by the feed water temperature. As the feed water temperature at the pre-heater outlet rises, the exergy efficiency of the deaerator increases. In this scenario, the mass flow of steam drives the deaerator, as pressure and mass flow of the blow down water in the pre-heater remain constant. When the feed water temperature is 34 °C, the exergy efficiency of the deaerator is 43%. As the temperature rises to 40 °C, the efficiency becomes 45.79%. Meanwhile, the total exergy efficiency increases from 26.18% to 26.43%.

5.5. Deaerator optimization

The main function of the deaerator is to remove the non-condensable gas from the system and to increase the feed water temperature before sending it to the boiler. This is done by receiving heat from the steam through the steam header. Therefore, it directly influences the amount of total steam that is eventually sent to the ethanol production system. The deaerator operates at specific pressure and mass flow. Here, the temperature of steam is assumed equal to the temperature of the steam generated from the boiler.

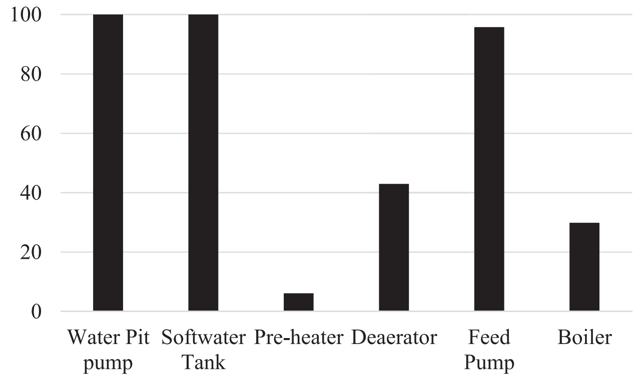

Fig. 5. Exergy efficiency of the individual components of the system.

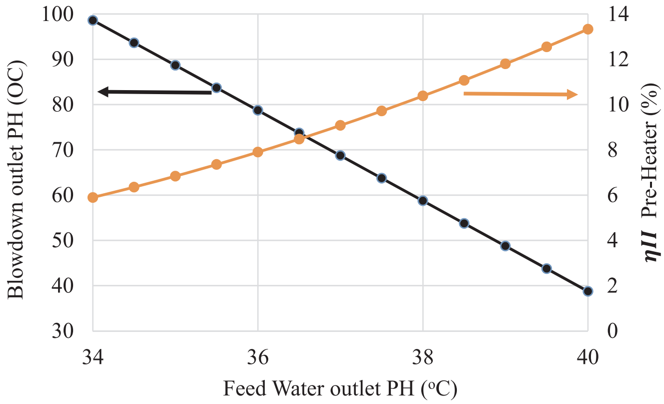

Fig. 6. Feed water temperature at the pre-heater outlet and exergy efficiency of pre-heater at a specific water blow down rate.

The variable that can be set in the deaerator is its pressure. In our system, the deaerator operates at a working pressure of 1.3 bar.

In this scenario, the deaerator pressure will be operated between 1.3 bar and 5 bar, as shown in Fig. 7. The temperature of blow down is at 96 °C within constant mass flow. Calculations show that there is an increase in exergy efficiency of the deaerator. The efficiency of the deaerator increases to a maximum of 60.25%. However, the total system exergy remains constant. This is because an increase in the pressure of the deaerator increases the mass flow of steam from the steam header to the deaerator. Increasing this steam flow from the header decreases the steam sent to the ethanol production plant.

6. Conclusion

This study aims to investigate the performance of the boiler in an ethanol production and proffer necessary solutions to improve the efficiency of the boiler. To this effect, the second law analysis is performed at the component level and the exergy efficiency of the individual components are determined from the daily plant operational data, such as vapor pressure, feed water, flue gas, and combustion chamber temperature, was obtained between 2015 and 2016 and was used in this study. The net exergy input into the boiler is 7783 kJ/s. The efficiency of steam production was analyzed using the second law efficiency of the cycle. The exergy efficiency of the boiler was found to be 26.19%, with 2214 kJ/s used in steam production, while 71.55% was lost to component irreversibility and waste heat from the pre-heater.

Exergy efficiency analysis of components reveal that the pre-heater has the lowest exergy efficiency at 6.13% and, hence, provides strong basis for its optimization in order to improve the efficiency of the boiler. The parametric optimization study shows that an increase in the outlet temperature of pre-heater results in an increase in the exergy efficiency of the pre-heater. The highest efficiency of 13.33% was achieved when the blowdown temperature of the pre-heater outlet was 40 °C, which shows that improving the pressure does not affect too much in the total efficiency of the boiler system.

In future works, some of which are currently underway, there are several investigations to improve total boiler efficiency by using approaches such as the re-design of pre-heater system, analysis of the chemical exergy in the furnace, and employing the flue gas from the stack outlet to increase the feed water temperature.

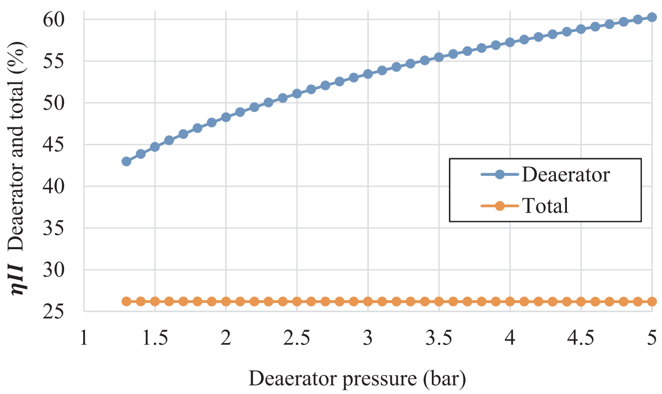

Fig. 7. Effect of deaerator pressure on deaerator and total boiler efficiency.

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