

SIMULATION STUDY OF GASIFICATION OF EMPTY FRUIT BUNCH (EFB) FOR ELECTRICITY GENERATION USING SUPERPRO DESIGNER

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ABSTRACT: Energy generation using non-renewable sources has always been an issue to the environment. To sustain the environment, gasification process using biomass as carbonaceous fuel is urged to reduce the dependency on coal or fossil fuel as the feed to generate energy. This project focused on identifying the best condition for running a gasification process using SuperPro Designer v9.5 software. The software was used to design the power plant by having the required unit operations such as gasification, cyclone separator, cooling, absorption, gas compression and gas expansion in their library. The unit operations were then arranged to build the plant and optimized by using Minitab v14 software to find out the best condition among the selected factors which are the fuel, steam, and oxidant streams into the gasifier for producing high yield of electrical energy. The result demonstrated that the biomass feed stream of two metric tons per hour of empty fruit bunch (EFB), one metric ton per hour of steam feed and zero-point five metric ton of air were enough to generate about 8246 kWh of electricity. Overall, all runs showed a good and approximately equal performance which indicate that the SuperPro designer simulation is reliable for analyzing gasification performance.

KEY WORDS: Gasification, EFB, Electricity generation, Simulation, and Optimization.

1. INTRODUCTION

The renewable energy plant is heavily dependent on the weather and season, and their topographical limitations concerning the construction site [1]. Although the drawbacks are somehow affected the continuity of the energy supplies, biomass is an abundant source of energy that has strong synergy with the current fossil fuel power plants especially coal and crude oil. Among the renewable sources, biomass is the promising resource to generate electricity through gasification process. Gasification process is not a newly developed industry to generate electricity. The gasification industry had already begun aiming to replace the imported fuels from the produced fuels, peat and wood waste [2]. The projects involve different types of reactors used to observe the best yield of electricity and more

economical value besides constructing the demonstration projects for the future prospect of biomass gasification in the country.

The process to convert gas to electrical energy requires a number of processes in the industry. To utilize the maximum potential from the abandoned biomass residuals, a process simulation is needed to model the conversion of biomass into electrical energy. The steps should comprise the pre-treatment stage. It is needed to dissect the wanted molecules from other unwanted molecules that reside in the main fruit before proceeding to gasification, cooling, cleaning and separation and then compression. Electrical energy comes from synthesis gas or in short 'syngas'. Syngas is known as a mixture of carbon monoxide, carbon dioxide and hydrogen.

Oil palm is very important commercial plant in Malaysia and Indonesia. It is extensively cultivated in Malaysia specifically for its diversity in the industrial of food, cosmetic, detergent, and others as their raw materials. Upon being used as the building block for the examples above, not all parts of this commercial plant being consumed to fit in their criteria are considered as palm oil waste. As a result, the oil palm industry has been contributing mass of oil palm biomass wastes in field and oil palm mills. The waste from mill includes the pressed fruit fibers (PFF), empty fruit bunch (EFB), oil palm shell (OPS), palm oil mill effluent (POME), whilst the other waste from the plantation comprises of oil palm trunks (OPT) and oil palm fronds (OPF).

Table 1: Electricity Generation Potential [3]

Product	Quantity (kiloton/year)	Potential generation (GWh)	Potential capacity (MW)
Rice mills	424	263	30
Palm oil mill effluent	31,500	1587	177
Bagasse	300	218	25
Palm oil mills	17,980	3197	365
Wood industry	2177	598	68
TOTAL	72,962	5863	665

Referring to Table 1, biomass that can be collected the most per year were palm oil mill effluent and palm oil mills with 31,500 and 17,980 kiloton per year [3]. Besides, the potential generation yield from both were also high compared to rice mills, wood industry and bagasse which indicates that palm oil-based biomass is preferred to be used for potential generation. From this comparison, the palm oil-based biomass Among the palm oil assorted types of waste, EFB in terms of availability, price, performance, and biodegradable nature are the strong reasons for it to be promoted as the energy source. Based on Table 2, EFB is the most produced in quantity among other palm oil biomass part from the palm oil mills. Therefore, it is suggested that EFB is the best biomass to be the feedstock for the gasification as it is the most generated biomass waste among the palm oil and contains higher potential generation compared to other biomass as it will be a promising approach for greater outcomes in terms of electricity produces or sustainable environment.

A good simulation should allow the user to identify the property of the biomass input, manage the unit operation, setting their operation conditions which also include the conversion of energy, display the composition of the results obtained. In addition, at the end of each process, the mathematical equations that built in the unit operation are also shown. Thus,

the simulation of gasification seems promising since it has a high result accuracy and can save a lot of resources for experimental purposes.

Table 2: Quantity of biomass from palm oil mills [3]

Biomass from palm oil	Quantity/ annum (MT/year)
Shell	4.7
Trunk	8.2
Mesocarp fiber (MF)	9.6
Fronds	12.9
Empty fruit Bunch (EFB)	15.8

Fig. 1 illustrates the proposed unit operations for EFB gasification to produce electricity. Cyclone separation, cooling and absorption are classed as the pre-treatment for the synthetic gas. Ash, other large particles of the components and the solvent gas that absorbed by the liquid stream are the waste generated from the plant. The objectives of this study are to simulate a process design plant that convert the biomass waste of EFB to electricity using SuperPro Designer v9.5 and to investigate the best condition for the gasifier to perform the gasification process in producing electricity.

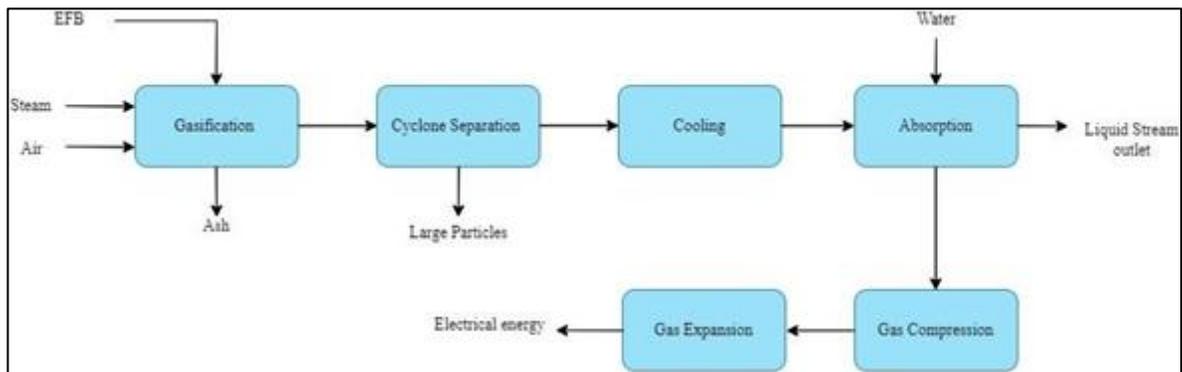


Fig. 1. Block flow diagram for the processes involved in the designed plant for gasification of EFB.

2. METHODOLOGY

The data for biomass input, conditions settings and controlled system data are obtained from the literature. To get the best output with the most feasible way for the gasification process, the simulation was done repeatedly for 12 times *i.e.* runs with different sets of flowrates inside the gasifier.

2.1. Identification of Unit Operations and Pure Components Involved from SuperPro Designer v9.5 Library

There are varieties of unit operation that are available in the software's library. After identifying the relevant unit operation based on the literature, gas cyclone separator, cooling, absorption, gas compression and gas expansion were chosen for the simulation. Most of the materials involved in the unit operations were registered in the software. For EFB, it must be first registered in the pure component library manually to be used inside the simulation. The molecular formula of EFB can be written as $\text{CH}_{0.14}\text{N}_{0.01}\text{O}_{1.17}\text{N}_{0.001}$ [4].

2.2. Gasification

The gasifier consists of three inlet streams and two outlet streams (Fig. 2). The fuel feed, which is on the top of the stream is labelled as EFB. Steam feed consists of purely water component while oxidant stream consists of air stream to the gasifier. Ash outlet stream allows the ash to be separated from the product gas stream. In this study, the input value is set on the mass flow instead of the volumetric flow. The unit for mass is Metric Ton (MT), volume (L), concentration (g/L), enthalpy (kW-h), temperature (°C) and pressure (bar). The time reference for flows is set to per hour. To run the gasifier, the elemental composition and the high heating value for the fuel stream needed to set up its [4].

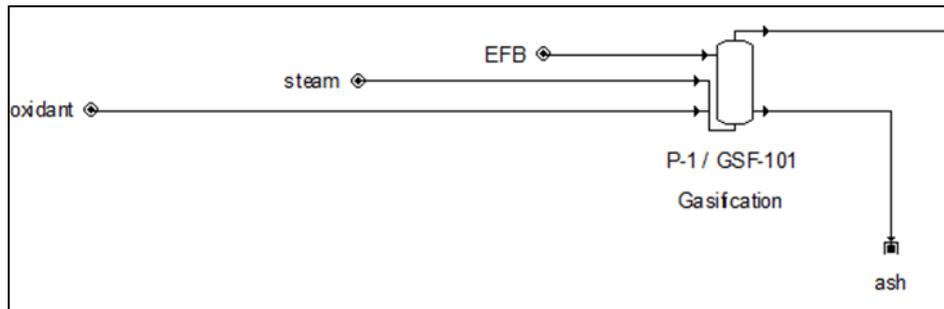


Fig. 2. Gasification unit operation.

Table 3: Composition and HHV of dry fuel components

Data	C (%)	H (%)	O (%)	N (%)	S (%)	Ash(%)	HHV(kcal/kg)
EFB	42.99	6.19	50.10	0.64	0.08	0.00	4294.93

The fuel combustion reaction is considered as the following Eq. (1):



where:

a = the atoms of H per atom of C

b = the atoms of O per atom of C

c = the atoms of N per atom of C

d = the atoms of S per atom of C

Meanwhile, the high heating value was estimated as the negative standard heat of combustion of the component (Eq. (2)).

$$\Delta H_{f,df} = HHV_{df} + n[\Delta H_{f,co} + \frac{a}{2}\Delta H_{f,H_2O} + d\Delta H_{f,SO_2}] \quad (2)$$

where:

$\Delta H_{f,df}$ = standard enthalpy of formation of dry fuel component (kJ/kg)

HHV_{df} = high heating value of dry fuel component (kJ/kg)

$\Delta H_{f\ CO_2}$ = standard enthalpy of formation of carbon dioxide (kJ/mol)

$\Delta H_{f\ H_2O}$ = standard enthalpy of formation of liquid water (kJ/mol)

$\Delta H_{f\ SO_2}$ = standard enthalpy of formation of Sulphur dioxide (kJ/mol)

The lower heating value (LHV) of the fuel components corresponds to the heat released per unit mass for fully combusted fuel and no heat recovery by the condensing produced vapor in the gasifier. The LHV was calculated as in Eq. (3):

$$LHV_{df} + HHV_{df} - n \frac{a}{2} \lambda_w \quad (3)$$

where:

n = atoms of C per kg of dry fuel component

LHV_{df} = low heating value of dry fuel component (kJ/kg)

λ_w = latent heat of vaporization of water at 1 bar and 25 °C (kJ/mol)

2.3. Gas Cyclone Separator

The velocity of the inlet gas was obtained and set at 30 m/s [5]. The other settings such as power, pressure drop, and operating throughput values could not be changed since they were set to be calculated by the software instead of being set by the user. The particle removal sizes varied from 750 microns up to 1000 microns. The range was chosen based on the literature [5] and for the component removal, only large size components such as ash, EFB palm oil and water were selected.

2.4. Cooling

Cooling unit operation received the product from the cyclone via its inlet stream. No components were removed inside the unit since it involved only in reducing the temperature of the inlet stream and its component before entering the next unit operation which is absorber. The energy balance for cooling is represented by Eq. (4):

$$Q = UA|\Delta T| = mc_p|\Delta T| \quad (4)$$

where:

Q = the cooling duty (kcal/h)

U = the overall heat transfer coefficient (kcal/h.°C.m²)

A = the heat transfer area (m²)

ΔT = the log mean temperature difference in the system (the driving force) (°C)

m = the mass flowrate of the stream (kg/h)

c_p = the specific heat capacity of the stream (kcal/kg.°C)

The value for U was specified by the user, while m and c_p values were calculated based on the stream flow and composition. Eq. (4) would be solved if the value of exit temperature was defined since it is equivalent to the value of ΔT . The exit temperature can be specified in the operating condition.

2.5. Absorption

The absorber consists of two inlet streams *i.e.*, liquid feed and vapor feed while there were two outlet streams *i.e.*, vapor output and liquid output. The vapor stream from the cooling unit operation was transferred into the absorber and in contact with the liquid feed. Based on the software, the selected gas which is carbon dioxide reacted with the liquid stream which is water and then it was separated from the vapor output and left the absorber through the liquid output as shown in Fig. 3.

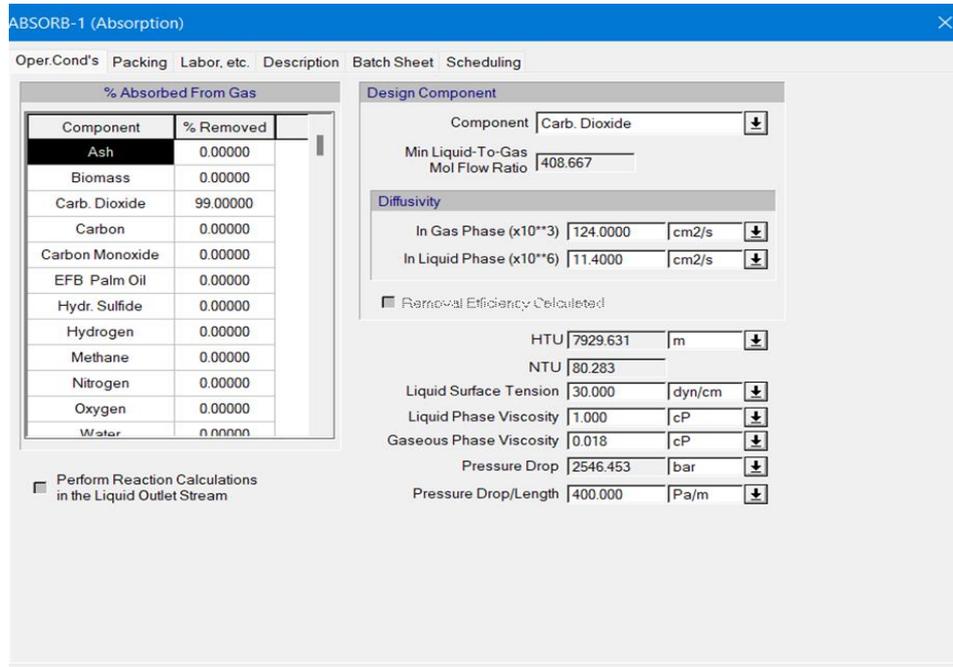


Fig. 3. Operating condition of absorber in SuperPro Designer v9.5.

2.6. Gas Compressor

For the gas compressor unit, centrifugal gas compression type was selected. The inlet stream was fed with the vapor stream from the absorber before being compressed inside the unit operation. The centrifugal gas compression requires high pressure increment due to the continuous conversion of angular momentum that imparted to the refrigerant vapor by a high-speed impeller into static pressure [6]. The static speed developed in the impeller passage for a single stage was determined by Eq. (5):

$$h = \frac{v^2}{g} \quad (5)$$

where:

h = static head developed, m

V = peripheral velocity of the impeller wheel, m/s

g = acceleration due to gravity, m/s²

Meanwhile, the increment of total pressure, ΔP as the refrigerant flows through was calculated by Eq. (6):

$$\Delta P = \rho gh = \rho V^2 \quad (6)$$

The high pressure to the input stream can be varied up to 20 bars [6]. In this study, the pressure change was set to 9 bars.

2.7. Gas Expansion

For the expansion model, isentropic analytical was used to the system as well as the built-in efficiency (condensate-free) model for the turbine efficiency per stage. To calculate the electricity generated, the synthetic gasses which are carbon monoxide, hydrogen and methane on each stage of the multi stages gas turbine was sum up after multiplying the flowrate with HHV value of respective gasses. Table 4 shows the HHV value of each gas.

Table 4: Syngas HHV value [7]

Syngas	HHV (MJ/kg)
Carbon monoxide	10.1
Hydrogen	142.2
Methane	55.5

Using Eq. (7), the power generated by gasification plant was determined:

$$\text{Power generated from a single syngas } \left(\frac{MJ}{h}\right) = \text{Syngas flowrate } \left(\frac{kg}{h}\right) \times \text{HHV value } \left(\frac{MJ}{kg}\right) \quad (7)$$

After multiplying the gasses flowrate with the HHV value, the values were added together according to each run to determine the amount of electricity generated.

2.8. Minitab v14 Software for Design of Experiment (DOE) and Analysis

To create the modelling design, the first step was setting the respond of the user goal. In this study, the response was set as the maximization of electricity generation by the gasifier. The settings of the inputs for the factors are:

Biomass: $1 \leq x \leq 2$

Steam: $0.01 \leq x \leq 1$

Oxidant: $0.1 \leq x \leq 1$

After completing the setting of the modelling design, the software allowed the user to fill the response of each run up to twelve with already filled inputs for each factors' column as shown Table 5.

Then, the analysis proceeded with ANOVA analysis and finally analyzed using the surface plot of the response on the combination of 2 factors that resulted in three possible surface plots.

Table 5: DOE table with filled input for each factor

Std Order	Run Order	Center Pt	Blocks	EFB (MT/h)	Steam (MT/h)	Oxidant (MT/h)
11	1	0	1	1.5	0.505	0.55
8	2	1	1	2	1	1
1	3	1	1	1	0.01	0.55
9	4	0	1	1	0.505	0.55
2	5	1	1	2	0.01	0.1
6	6	1	1	2	0.01	1
7	7	1	1	1	1	1
3	8	1	1	1.5	1	0.55
4	9	1	1	2	1	0.55
10	10	0	1	1.5	0.505	1
5	11	1	1	1	0.01	1
12	12	0	1	1.5	0.01	1

3. SUPERPRO DESIGNER SIMULATIONS RESULT

The performance of gasifier, compressor and multi-stages gas turbine were analyzed to determine the best condition for the gasification plant to be operated. Cyclone separator, cooling heat exchanger and absorber are not discussed in this part and the settings were made based on the literature. Only gasifier input stream and energy yield from gas turbine are included and discussed under this section. The best condition for the gasification process is defined when it generates high electrical energy with the optimum amount of input streams from EFB, steam and oxidant streams that enter gasifier. Fig. 4 indicates the overall gasification design plant.

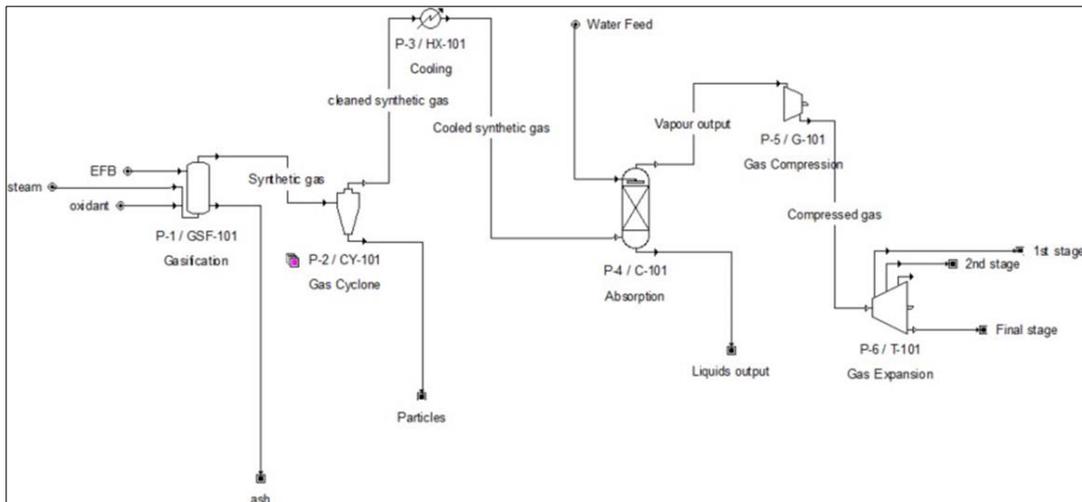


Fig. 4. Gasification design plant.

The experiment was carried out for 12 times with different flowrate compositions of fuel, steam and oxidant as in Table 6.

Table 6: Simulation results for each run

Running order	Fuel stream flowrate (MT/h)	Steam stream flowrate (MT/h)	Oxidant stream flowrate (MT/h)	Electricity generated (kWh)
1	1.5	0.505	0.55	5861.48
2	2	1	1	8839.86
3	1	0.01	0.55	3624.66
4	1	0.505	0.55	4499.98
5	2	0.01	0.1	5626.53
6	2	0.01	1	7067.23
7	1	1	1	3999.49
8	1.5	1	0.55	6904.36
9	2	1	0.55	8246.10
10	1.5	0.505	1	6536.78
11	1	0.01	1	4381.99
12	1.5	0.01	1	5721.76

From Table 6, the highest electrical energy produced by the second run. Under this run, all parameters were set to the maximum value of the range that have been selected. Since all streams were at their highest allowable range, the combustion of the fuel and the reactions with the steam and air inside the gasifier will be at the maximum and hence producing the largest electrical yield compared to other runs from the gasification design plant.

Table 7: Flowrate and mass composition of syngas according to run order

Run order	CO		H ₂		CH ₄		Electricity generated (kWh)
	Flowrate (kg/h)	Mass Comp. (%)	Flowrate (kg/h)	Mass Comp. (%)	Flowrate (kg/h)	Mass Comp. (%)	
1	436.366	41.3247	79.30036	7.5099	97.61274	9.2441	5861.48
2	589.096	35.3022	118.0496	7.0742	163.7288	9.8116	8839.86
3	525.9954	51.2922	46.38373	4.5231	20.54873	2.0038	3624.66
4	314.234	35.2323	60.45037	6.7778	79.82146	8.9497	4499.98
5	539.5127	68.8646	77.29676	9.8663	68.73544	8.7735	5626.53
6	1003.462	52.1237	91.17962	4.7362	42.18576	2.1913	7067.23
7	384.6482	29.4689	31.96406	2.4488	107.5299	8.2381	3999.49
8	296.2374	29.4919	84.64998	8.4273	177.0528	17.626	6904.36
9	408.86	35.3041	104.4473	9.0188	192.8658	16.653	8246.10
10	645.4667	40.3224	89.27374	5.5769	77.80989	4.8608	6536.78
11	773.4235	47.876	50.56006	3.1298	13.94502	0.8632	4381.99
12	886.777	50.1501	71.21788	4.0276	27.29186	1.5434	5721.76

According to Table 7, the ninth run has the most hydrogen gas mass composition in the stream compared to others with 9.0188% of total syngas in gas turbine unit. The ninth stream also have less mass composition of CO gas with only 35.304% of total syngas in the stream while other runs comparatively above 40% of CO mass composition in a single stream, and the second highest mass composition with 16.653 % of methane in the run. Compared to the second run, the ninth run generated less electricity with 8246.10 kW/h than 8839.86 kW/h. However, it used much less amount of air in the oxidant stream than the second run. Consequently, it will be more efficient to use less resources to produce relatively a higher yield even if it is not the highest.

4. DOE ANALYSIS BY MINITAB SOFTWARE

The analysis focused on investigating on the factors that affecting the electrical energy produced in the gasification design plant. The factors that were analyzed are EFB, steam and oxidant streams that are basically the input streams into the gasifier.

The DOE comprised of linear fit model, general fit model of ANOVA analysis and surface plots of response versus the factors. Fig. 5 summarizes the linear fit model from Minitab v14 software.

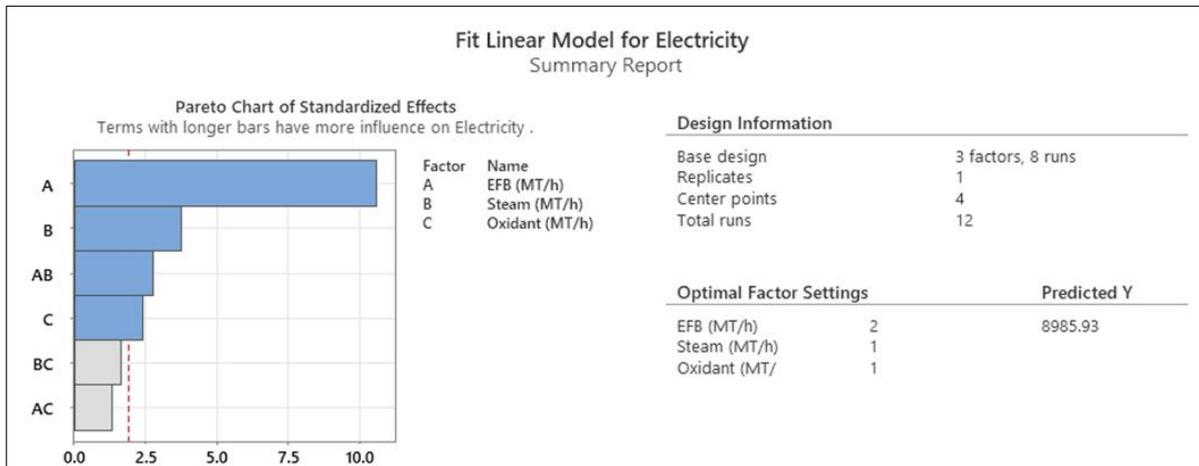


Fig. 5. Summary report on Fit Linear Model for electricity.

Based on Fig. 5, the most influential factor for generating electricity for the gasification plant is the EFB flowrate compared to the steam, EFB and steam, oxidant, steam, and oxidant, and EFB and oxidant.

Table 8: ANOVA of Gasification Process

Source	DF	Adj SS	Adj MS	F-Value	P-Value
EFB (MT/h)	2	20724592	10362296	33.13	0.001
Steam (MT/h)	2	1438843	719421	2.30	0.196
Oxidant (MT/h)	2	2175168	1087584	3.48	0.113
Error	5	1563849	312770		
Total	11	30063480			

For general linear model on ANOVA analysis, the F-value was used to determine the statistical significance of the simulation while P-values were implemented to check the significance on each variable. P-value must be less than 0.05 in order to confirm that the design model is 5% significant and reliable [8]. Any P value greater than 0.10 is considered insignificant. Thus, from Table 8, it can be concluded that EFB flowrate stream is significant to impose major influence on the amount of electricity generated compared to the steam and oxidant flowrate of the system.

For the surface plots results, there are three diverse set of plots to be compared. Each of the surface plot were conducted with the same response on the z-axis to display the results of distinct factors affecting the response.

From Fig. 6, it was observed that the oxidant stream reached the lowest yield on 0.5 MT/h while feeding with minimum amount from the steam stream but achieved it peaks of

electricity generation when supplied with 1.0 MT/h of steam. However, EFB on the fuel stream was observed to increase the electricity generation at 2.0 MT/h of flowrate and 0.5 MT/h of oxidant supplied as illustrated in Fig. 7 and reach the peak of electrical energy with 8839.86 kW/h also at 2 MT/h but with 1.0 MT/h of steam (Fig. 8).

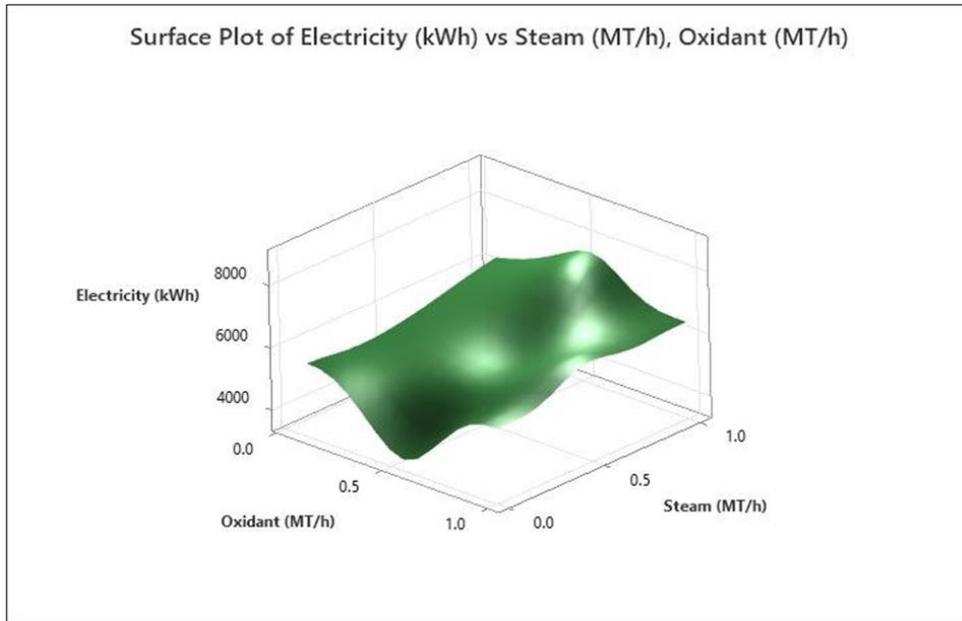


Fig. 6. Surface plot of electricity vs. steam and oxidant flowrates.

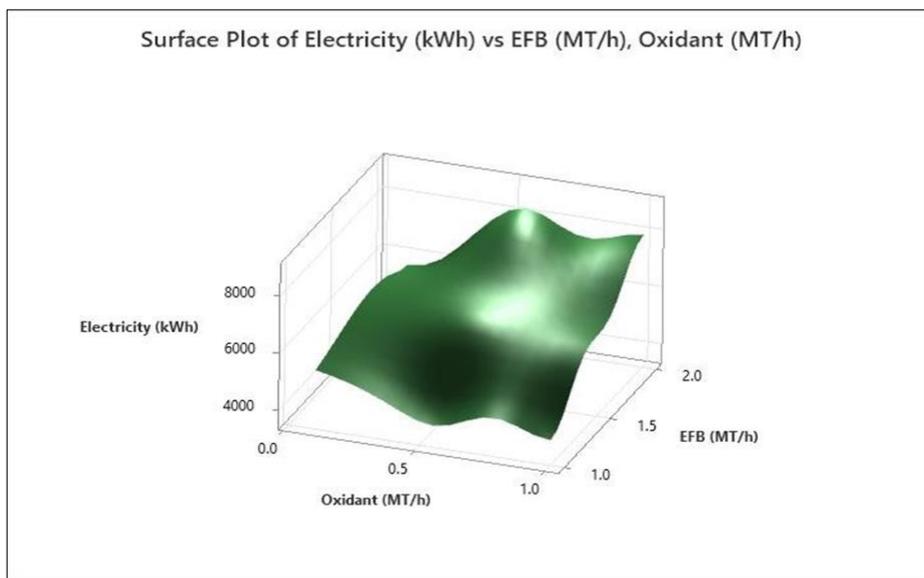


Fig. 7. Surface plot of electricity vs. EFB and oxidant flowrates.

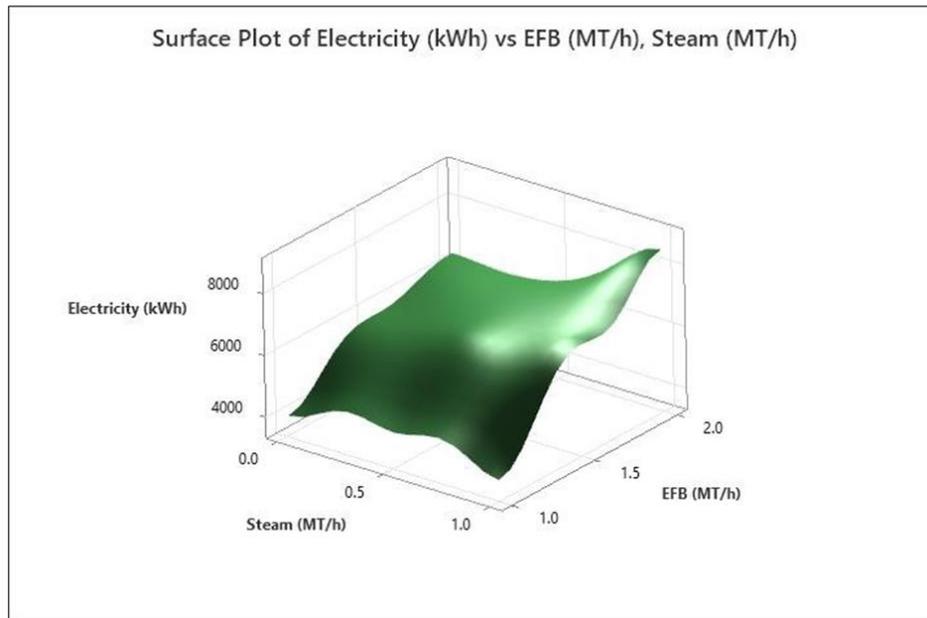


Fig. 8. Surface plot of electricity vs. EFB and steam flowrates.

Finally, based on the results of the 12 runs in SuperPro Designer v9.5 and the surface plot graphs, the ninth run with EFB of 2 MT/h, 1 MT/h of steam and 0.55 MT/h of oxidant is the best condition of the gasifier inlet feeds because air from the oxidant stream is the limiting reactant, which it will slowly stops abruptly from reacting with other components as it have produce electricity of 8,246 kW/h with optimum number of resources.

5. CONCLUSION

Simulation in SuperPro Designer software is a reliable tool to present a gasification process design to generate electricity. The software has built-in values and equations that calculates the problems for the input instead of manually input by the user. The unit operations for generating electricity as simulated in SuperPro Designer v9 include gasifier, gas cyclone, cooling heat exchanger, absorber, gas compressor and finally multi-stage gas turbine. Analysis of DOE by Minitab v14 showed that EFB flowrate was the most influential factor for the gasification process compared to the steam and oxidant factor or any other combinations of two from the three factors.

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