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Optimization of oil palm empty fruit bunch gasification temperature and steam to biomass ratio using response surface methodology

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Abstract. An experimental work of empty fruit bunch gasification was conducted by using the bubbling fluidized bed to study the effect of the gasification temperature and steam biomass ratio (SBR) on the synthesis gas yield, Lower Heating Value (LHV) and Cold Gas Efficiency (CGE). Response Surface Methodology (RSM) was used to design the gasification experiment from the temperature range of $800 - 1000°C$ and SBR range of $0.5 - 1.5$. Thirteen number of runs were generated based on Central Composite Design (CCD) with five replicated center points. Three regression models for predicting synthesis gas yield, LHV and CGE were developed and Analysis of Variance (ANOVA) was performed in this study. From ANOVA, the most influencing factor was gasification temperature which obtained higher F-value compared to SBR. The numerical optimization was also conducted in order to obtain the optimum condition to maximize the synthesis gas yield, LHV and CGE. From numerical optimization, gasification temperature of 800 °C and SBR of 1.14 were determined as the optimum condition which contributes to the maximum synthesis gas yield, LHV and CGE which are 1.25 Nm^3/kg, 10.49 MJ/Nm^3 and 90.72% respectively. The percentage error between the predicted and actual value of response variables was calculated and the error obtained lesser than 1%. Thus, it confirmed that the models obtained can be used to optimize the gasification of the empty fruit bunch.

1. Introduction

Recent issues on the limitation of fossil fuels and high level of air pollution made renewable energy technologies become more importance [1]. Currently, the depletion of fossil fuel has become global concerns where the energy sources are mainly depending on fossil fuels. Besides, the development of the industries and the growth of population especially in Malaysia are also degrading the environmental quality due to the excessive utilization of fossil fuels [2-3]. Thus, it is necessary to focus on the alternative of renewable energy from green and clean sources in order to obtain a better quality of the environment [3]. Thus, biomass has been introduced to the world as promising clean and green energy sources to replace the use of fossil fuels. The utilization of biomass does not increase carbon dioxide in the atmosphere as it absorbs the same amount of carbon as it releases during the photosynthesis process [3]. In Malaysia, oil palm wastes are the primary biomass resources which contain of empty fruit bunch (EFB), palm kernel shell (PKS) and oil palm fronds (OPF). Among oil palm wastes, EFB is found to have the highest amount produced which are 17.08 million tons per year [4]. Currently, EFB was utilized for the production of fertilizer for agricultural purposes. However, the fertilizer production only covered

small amounts of EFB where the unused one are being left rotten. Meanwhile, palm oil mills used EFB for combustion process in their boilers in order to generate electricity which is used to power the milling process [5].

Thermochemical conversion of biomass such as combustion, pyrolysis, liquefaction and gasification into biofuels and useful chemicals would solve the waste problem and energy crisis. Biomass gasification is the process that converts feedstock to fuel gas in the presence of the gasifying agent such as air and steam. However, steam is found to be more efficient as it produces reaction products with higher heating value compared to air [6]. There are several gasification technologies such as fixed bed, fluidized bed and entrained flow gasifiers. However, fluidized bed gasifier promotes heat transfer to the biomass particle which contributes to enhance the reaction rates and conversion efficiency [7]. There are two types of fluidized bed gasifier which are bubbling and circulating fluidized bed. Compared to circulating fluidized bed, bubbling fluidized bed has a minimum fluidizing velocity to promote the mixing of the hot bed material [8]. For biomass gasification, the bubbling fluidized bed gasifier has a simple process thus explains why it was chosen in this work. Biomass gasification is a noteworthy process because it produces high quality of synthesis gas mainly hydrogen, carbon monoxide, carbon dioxide and methane which currently use as fuel for internal combustion engines and fuel cells [6]. There are several parameters that influence the gasification performance as well as synthesis gas production such as gasification temperature and steam to biomass ratio (SBR). Hence, the optimization of the biomass gasification must be conducted in order to obtain the best gasification temperature and SBR.

Response Surface Method (RSM) is the method of experimental design which generate regression equation model by using analysis of variance (ANOVA) of responses and process variables. RSM with Central Composite Design (CCD) can investigate the influence of the interaction of variables on the responses by using Design Expert Software. In previous literature, Razi et al. [1] used RSM to investigate the effect of gasification temperature, biomass blending ratio and steam flow rate on response variables which were gas, tar and char yield from the co-gasification process of pretreated PKS and pretreated Malaysian low rank coal. Besides, Shahbaz et al. also used RSM with CCD to study the influence of temperature, feedstock particle size, CaO/biomass and coal bottom ash on methane production from PKS gasification [9]. However, the optimization of the gasification performance in terms of synthesis gas yield, lower heating value and cold gas efficiency is not carried out by other researchers yet. The higher synthesis gas yield, LHV and CGE obtained from the gasification will indicate the higher efficiency of the gasification performance. Therefore, the objective of this work is to determine optimum operating condition (gasification temperature and steam to biomass ratio) of the gasification of the empty fruit bunch (EFB) in order to maximize the synthesis gas yield, lower heating value (LHV) and cold gas efficiency (CGE). The raw EFB will be used in a bubbling fluidized bed reactor and the experiment will be designed by using Central Composite Design (CCD) and the number of experimental runs will be obtained. Furthermore, the optimization of the process parameters was carried out using Response Surface Method (RSM) in Design Expert software.

2. Materials and Methods

2.1. Materials
Raw EFB was used in this work, which was obtained from Lepar Hilir Palm Oil Mill, Kuantan, Pahang. The sample was dried in the oven for about 4 hours at 105°C to reduce the moisture content from 23.44% to 4.63%. After drying process, the dried EFB was grinded and sieved to the particle size of 0.5 – 1.0 mm and stored in an air-tight container to maintain its moisture content. The higher heating value (HHV), proximate and ultimate analysis of EFB were obtained from the previous work on raw EFB as shown in the Table 1 and Table 2 [10]. Ultimate analysis is the composition of the element in the EFB while proximate analysis is the percentage of the moisture content, fixed carbon, volatile matter and ash of the EFB [11].

Table 1. The proximate analysis of the empty fruit bunch (EFB) [10]

Proximate Analysis (wt%)	Weight percentage (wt%)
Moisture Content	4.63
Volatile Matter	48.44
Fixed Carbon	39.23
Ash	7.70

Table 2. The ultimate analysis of the empty fruit bunch (EFB) [10]

Ultimate Analysis (wt%)	Weight percentage (wt%)
C	54.63
H	5.63
N	6.37
S	0.21
O	36.04
HHV (MJ/kg)	19.60

2.2. Experimental gasification of empty fruit bunch
The gasification of EFB was carried out using a bubbling fluidized bed gasifier which was made from stainless steel. The gasifier with a bed diameter of 60 mm and height of 850 mm is used and silica sand is employed as the bed material since it has high specific heat capacity and could operate at higher temperature [7]. The EFB feedstock with flow rate of 0.25 – 0.4 kg/h was fed into the reactor by using a screw feeder conveyor. The gasifying agent used in this work was steam which was flushed from the bottom of the reactor. Then, the gasifier was heated by using an electric furnace to the desired temperature. The volatile product exited from the top of reactor and proceeded to the separation process at the cyclone separator. The purpose of the separation process is to separate the volatile product from ash and tar. After the separation process, cleaning and drying process were made using a dry ice trap and stored in a gas sampling bag.

2.3. Design of experiment using Response Surface Methodology (RSM)
Response Surface Methodology (RSM) was chosen for experimental design using Design Expert 7 software. The factors of this study (gasification temperature and steam to biomass ratio) were optimized by using Central Composite Design (CCD) in RSM. The gasification temperature in the range from 800 – 1000°C and SBR in the range from 0.5 – 1.5 were selected as the range of the factors based from the literature [12]. The experiment was designed by the software with 13 number of runs for each response variable including 5 center points as shown in Table 2. The number of runs was calculated by [1]

$$N = 2^n + 2n + n_c \qquad (1)$$

Where N is the number of runs, n is the number of factors used which are gasification temperature and SBR, and n_c is the number of central points. The responses that were measured are synthesis gas yield, lower heating value (LHV) and cold gas efficiency (CGE). The ANOVA analysis were used to evaluate the analysis of the interaction and individual effect of factors on each response. The regression model and response models in 3D plot surface were also evaluated. The EFB gasification using bubbling fluidized bed was conducted as designed experiments and synthesis gas produced was collected. From the gasification result, the synthesis gas yield was calculated

$$Syn_{yield} = \frac{V_g}{M_f} \qquad (2)$$

Where V_g is the volume of the synthesis gas obtained from EFB gasification and M_f is the mass of the EFB used. The energy content in biomass without heat of condition of water is expressed as lower heating value (LHV) and is defined as [4]

$$LHV_{yield} = (30x_{CO} + 25.7x_{H_2} + 85.4x_{CH_4}) \times 4.2 \qquad (3)$$

Where x is the mole fraction of the produced gas species. Cold gas efficiency (CGE) is also required to evaluate the gasification performance and is calculated by [4]

$$CGE(\%) = \frac{LHV_{gas} \times Syn_{yield}}{HHV_{feedstock}} \times 100 \qquad (4)$$

Where HHV is the higher heating value of the EFB which was shown in Table 1. Table 3 shows the values of synthesis gas yields, LHV and CGE calculated based on 13 different operating conditions for EFB gasification.

Table 3. Experimental design for EFB gasification at different temperature and SBR

No of Run	Gasification Temperature (°C)	SBR	Synthesis gas yield (Nm³/kg)	LHV (MJ/Nm³)	CGE (%)
1	800	1.00	1.10	9.97	85.67
2	1000	1.00	1.30	10.31	91.35
3	800	1.00	1.08	10.02	84.36
4	1000	0.50	1.16	9.54	82.76
5	800	1.00	1.11	9.91	85.06
6	600	0.50	0.85	7.84	67.38
7	800	1.50	1.20	10.08	82.78
8	800	1.00	1.09	9.90	83.84
9	1000	1.50	1.23	10.23	89.24
10	600	1.50	0.93	9.28	78.54
11	600	1.00	0.90	8.85	73.21
12	800	1.00	1.07	10.02	85.03
13	800	0.50	0.98	8.63	76.28

3. Result and Discussion

3.1. Statistical analysis

The ANOVA was performed for the evaluation of the response variables with the possible interactions. The validation of the developed model is indicated by P-value which is the probability value from the ANOVA while F-value is Fischer's F-test value which indicates the influences of process parameter on the response. As shown in Tables 3-5, all model found to be significant with high value of F-value and low P-value. For synthesis gas yield, the gasification temperature is more influence with higher F-value (89.50) compared to SBR (12.01). The gasification temperature also is the most influence factor for response variables LHV and CGE with higher F-value compared to the SBR. Based on the result obtained, the synthesis gas yield increased to a maximum value at temperature 1000°C due to the further cracking of liquid and enhanced char reaction with steam that reduce the amount of liquid and char. However, the excessive of steam will reduce the temperature as it will absorb heat thus reducing the synthesis gas yield [1][9]. Furthermore, the results also showed the lack of fit for the three developed models are significantly larger than the pure error. Thus, the lack of fit is signified for all of the terms in the model which are fitted to the response variables.

Table 4. Result of ANOVA for synthesis gas yield

Source	Sum of squares	df	Mean square	F-value	P-value	
Model	0.20	5	0.040	20.08	0.0005	Significant
A-Temperature	0.17	1	0.17	89.50	<0.0001	
B-SBR	0.023	1	0.023	12.01	0.0105	
AB	2.500E-005	1	2.500E-005	0.013	0.9119	
A^2	8.710E-003	1	8.710E-004	0.46	0.5201	
B^2	2.128E-003	1	2.128E-003	1.12	0.3250	
Residual	0.013	7	1.900E-003			
Lack of fit	0.012	3	4.099E-003	16.40	0.0103	Significant
Pure Error	1.000E-003	4	2.500E-004			
Cor Total	0.21	12				
R-squared	0.9369					

Table 5. Result of ANOVA for LHV

Source	Sum of squares	df	Mean square	F-value	P-value	
Model	6.40	5	1.28	79.67	<0.0001	Significant
A-Temperature	2.82	1	2.82	17529	<0.0001	
B-SBR	2.14	1	2.14	133.00	<0.0001	
AB	0.14	1	0.14	8.76	0.0211	
A^2	0.19	1	0.19	11.86	0.0108	
B^2	0.66	1	0.66	40.88	0.0004	
Residual	0.11	7	0.016			
Lack of fit	0.099	3	0.033	9.92	0.0253	Significant
Pure Error	0.013	4	3.330E-003			
Cor Total	6.51	12				
R-squared	0.9827					

Table 6. Result of ANOVA for CGE

Source	Sum of squares	df	Mean square	F-value	P-value	
Model	501.04	5	100.21	42.16	<0.0001	Significant
A-Temperature	325.90	1	325.90	137.12	<0.0001	
B-SBR	97.12	1	97.12	40.87	0.0004	
AB	5.48	1	5.48	2.30	0.1728	
A^2	4.84	1	4.84	2.04	0.1967	
B^2	45.83	1	45.83	19.28	0.0032	
Residual	16.64	7	2.38			
Lack of fit	14.64	3	4.88	9.80	0.0258	Significant
Pure Error	1.99	4	0.50			
Cor Total	517.67	12				
R-squared	0.9679					

The synthesis gas yield, lower heating value (LHV) and cold gas efficiency (CGE) are important for the biomass gasification as the key response variables [13]. Hence, this study investigated the influence of gasification temperature (X_1), steam to biomass ratio (X_2) and the interaction of both process variables to the synthesis gas yield (Y_1), LHV (Y_2) and CGE (Y_3). Other than F-values and P-values, the precision of the model towards the actual data was further evaluated by using regression coefficient (R^2). The value of R^2 obtained were 0.9369, 0.9827 and 0.9679 for synthesis gas yield, LHV and CGE respectively which close to 1. This indicates the reliability of the regression models since the validity of regression model is evaluated based on $R^2 > 0.75$ [14]. Furthermore, the residual shows in Table 4 – 6 indicate the difference of predicted and actual values of the response variables. The developed regression models are shown below:

$$Y_1 = -0.11391 + 1.57701\text{E-}03X_1 + 0.36540X_2 - 2.5\text{E-}07X_1X_2 - 4.43966\text{E-}07X_1^2 - 0.11103X_2^2 \quad (5)$$

$$Y_2 = -1.65575 + 0.015803X_1 + 6.59402X_2 - 1.875\text{E-}03X_1X_2 - 6.56466\text{E-}06X_1^2 - 1.95034X_2^2 \quad (6)$$

$$Y_3 = 0.096782 + 0.10149X_1 + 49.99425X_2 - 0.0117X_1X_2 - 3.30862\text{E-}05X_1^2 - 16.29379X_2^2 \quad (7)$$

The residuals obtained for all three response variables were acceptable and indicated the significant of all the regression models.

To visualize the interaction between interaction between two process variables on the response variable, 3D surface plots are studied as shown in Figure 1. The graphical results show that synthesis gas yield is increased with increasing of gasification temperature and SBR. Among those two variables, gasification temperature is the most significant process parameter which influence the synthesis gas yield. At higher temperature, endothermic reactions such as steam methane reforming contributes to more synthesis gas production. Meanwhile, from Figure 1(b), the higher LHV obtained at higher gasification temperature and SBR. At higher temperature, the composition of hydrogen, carbon monoxide and methane gases produced were higher which contributes to the increasing of LHV as shown in Equation (2). The LHV also affected by the SBR which denoted a dominance of steam methane reforming reaction. For CGE, it can be observed that CGE is enhanced by a rise in the gasification temperature as well. However, the increasing of SBR which also increase the oxygen content in the gasifying atmosphere led to slower increment of gasification temperature as oxidation reactions are

favored to detriment of the gasification reactions [15]. Figure 1(c) clearly shows that the interaction of the gasification temperature and SBR affected the value of CGE.
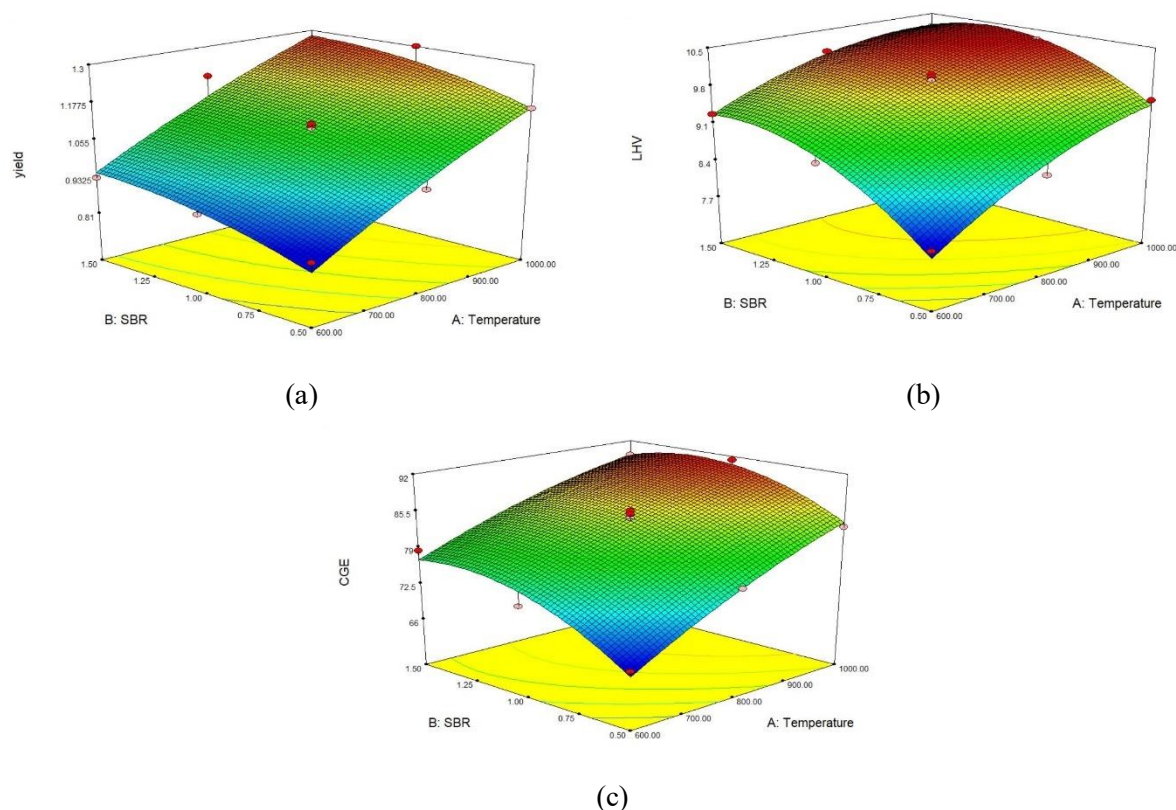

(a)

(b)

(c)

Figure 1. The response models in 3D surface plot for responsive variables (a) synthesis gas yield, (b) lower heating value (LHV) and (c) cold gas efficiency (CGE)

3.2. Process optimization and validation

Table 7. The predicted and actual values of synthesis gas yield, LHV and CGE

	Predicted	No of Runs			Average	Error (%)
		1	2	3		
Synthesis gas yield (Nm^3/kg)	1.26	1.27	1.25	1.24	1.25	0.8
LHV (MJ/Nm^3)	10.43	10.27	10.69	10.52	10.49	0.57
CGE (%)	90.99	90.48	90.64	91.05	90.72	0.30

The optimum operating condition for the gasification process was obtained from the numerical optimization using Design Expert software. From optimization, the optimum operating condition was specified at gasification temperature of 800°C and SBR of 1.14 for all responses. The desirability value of 1.000 is obtained from numerical optimization in Design Expert software indicates that the design is suitable for use. Actual experiments were done based on the optimum operating conditions obtained in order to verify the optimum operating condition. Gasification experiments were performed 3 times at gasification temperature of 800°C and SBR of 1.14 and the average value is presented for synthesis gas yield, LHV and CGE. The percentage errors between actual and predicted value of all experiment are shown in Table 7. It can be observed that the percentage errors were in acceptable range which was

lesser than 1%. This confirms that the optimum operating condition generated from Design Expert software is indeed reliable in producing maximum synthesis gas yield, LHV and CGE for EFB gasification process.

4. Conclusion

In this study, the biomass gasification of EFB was carried out using bubbling fluidized bed. The effect of gasification temperature from 800 - 1000°C and steam to biomass ratio (SBR) from 0.5 – 1.5 were studied using Response Surface Methodology (RSM). The gasification temperature and SBR are selected as factors and synthesis gas yield, lower heating value (LHV) and cold gas efficiency (CGE) are used as response variables in this work. The experimental work was designed in Design Expert software by using Central Composite Design (CCD). Based on numerical optimization study, the optimum operating condition for EFB gasification was found at gasification temperature of 800 °C and SBR 1.14. The EFB gasification was conducted again based on generated optimum operating conditions in order to verify the synthesis gas yield, LHV and CGE. The average results obtained from the experimental work are 1.25 Nm^3/kg, 10.49 MJ/Nm^3 and 90.72% for synthesis gas yield, LHV and CGE respectively. The percentage errors between predicted and actual values of synthesis gas is 0.8%, LHV is 0.7% and CGE is 0.3% which proved that the developed model is valid and optimum operating condition obtained is significant.

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