

Air gasification of oil palm waste over dolomite in a fluidized bed

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Abstract: Air gasification of oil palm empty fruit bunch was carried out in a fluidized bed gasifier. Calcined dolomite was used as the catalytic bed material. The effect of bed temperature (650–1050 °C) on the quality of the producer gas was examined. During the gasification experiment, a producer gas with improved quality was obtained at high temperatures, but agglomeration of the bed material was realized as the major concern at temperatures above 850 °C. Thus, the temperature was reduced and the quality of the product gas was assessed through a set of experiments designed by response surface methodology. The bed temperature ($T = 650\text{--}850$ °C) and equivalence ratio ($ER = 0.18\text{--}0.28$) were selected as the 2 process variables. The experimental results were reasonably fitted to the developed model. The optimum conditions were $T = 850$ °C and $ER = 0.22$ at which the $HHV = 5.39$ (MJ/m³) could be attained without any agglomeration of the bed material.

Key words: Gasification, fluidized bed, dolomite, palm empty fruit bunch

1. Introduction

Finding alternative sources of energy is a global concern, especially for countries lacking conventional fuel resources. Various sources of renewable energy are regarded as potential candidates to overcome the problem of depletion of fossil fuels as well as global warming caused by the emission of greenhouse gases. Production of energy from lignocellulosic feedstocks is receiving worldwide attention, amongst various renewable energy resources (Sims et al., 2010; Mohammadi et al., 2011).

Palm (*Elaeis guineensis* Jacq.) planting has experienced fast growth during recent decades. Palm is the dominant agricultural crop in Southeast Asia and South America (De Souza and Spinelli, 2009; Idris et al., 2010). Only in Malaysia, 4.49 million hectares of land is under palm cultivation, producing 17.73 million tons of palm oil annually. Palm oil mill factories generate huge amounts of lignocellulosic biomass after extracting oil from the palm fruit. It has been estimated that while producing 1 ton of palm oil, 1.07 tons of empty fruit bunch (EFB) is generated.

Recently, biomass gasification has been a source of hope for production of second generation biofuels from nonfood resources. Gasification is one of the thermal processes that converts the lignin component of biomass along with the cellulose and hemicellulose into synthesis gas. The gaseous product obtained from the gasification can be potentially used after cleaning up to run internal combustion engines or produce a large variety of biofuels including synthetic diesel and ethanol through Fischer–Tropsch conversion (Alauddin et al.,

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2010; Mohammadi et al., 2011). Thus, the purity and high quality of the producer gas is of utmost importance for its consequent applications. In traditional gasifications, high percentages of undesired products and tar were generated during the gasification process. Long-term application resulted in damage such as corrosion and blockage in the system and reduction in the overall efficiency. To avoid the formation of considerable amounts of tar and low quality gas products, the gasification process used to be performed at high temperatures. However, use of high temperatures could induce agglomeration of the bed materials, especially in the case of feedstocks with high alkali contents. From the 1980s onwards, catalytic gasification has attracted attention with the aim of improving the producer gas composition, reducing the tar content, and accelerating the reaction time (Corella et al., 2004; Hu et al., 2006).

Dolomite [$\text{CaO.MgO}(\text{CO}_3)_2$] as a cheap and plentiful catalyst in biomass gasification has been employed by several researchers in power plants (Olivares et al., 1997; Hu et al., 2006; Corella et al., 2008). Dolomite is an adaptable catalyst with air, steam, and a mixture of steam and oxygen as medium gas (Narvaez et al., 1996; Olivares et al., 1997; Corella et al., 2004; Hu et al., 2006). It has also been utilized as a suitable bed material in commercial fluidized bed gasifiers (Salo and Horvath, 2009). Dolomite has proved its ability to avoid or reduce the formation of agglomerates, especially in feedstocks with high alkali contents (Gusta et al., 2009). Moreover, in situ catalytic reactions promoted by dolomite positively affect the cracking of tar and enhance the quality of the producer gas (Narvaez et al., 1996; Olivares et al., 1997; Xie et al., 2010; de Andrés et al., 2011). It has been reported that the presence of 20–30 wt% dolomite in the gasifier bed significantly improves the quality of the producer gas and prevents bed agglomeration (Gil et al., 1999). Corella et al. (2004) studied the effect of various catalytic bed materials on agglomeration with high alkali content biomass. They concluded that dolomite has the ability to avoid bed agglomeration up to 900 °C. Another investigation was carried out by Zevenhoven-Onderwater et al. (2001) in a lab scale pressurized fluidized bed gasifier with reed canary grass as feedstock and various bed materials. In their experiment, no agglomeration was observed with dolomite up to 900 °C, whereas silica sand formed agglomerates at 701 °C and caused defluidization in the gasifier.

Previous investigations showed that agglomeration of the bed material is considered the major concern in gasification of EFB, especially at high temperatures (Lahijani and Zainal, 2010). Thus, in the current study, dolomite was used as an alternative bed material to reduce the sintering tendency of the bed. The objective of this investigation was to maximize the percentage of combustible gases in the producer gas as well as the carbon conversion efficiency, HHV, dry gas yield, and cold gas efficiency. Considering the trade-off relationship between these gasification performance indexes, it is almost impossible to have all these outputs at their optimum values at the same time. Thus, the obtained experimental results were introduced into a response surface methodology (RSM) model under central composite design (CCD) to define the optimum conditions. RSM is a standard mathematical and statistical method for modeling and optimizing problems. Optimization of the experimental conditions using RSM has been found to be a useful way to study the interactions between 2 or more variables (Kumar et al., 2009; Feroso et al., 2010; Zinatizadeh et al., 2010). This method uses quantitative data from proper experiments to determine the optimum operating conditions and models the regression equations. In the present investigation, 2 major and effective gasification parameters, bed temperature and equivalence ratio (ER), were considered to determine the conditions that satisfy the optimum operating conditions.

2. Materials and methods

2.1. Experimental set-up

The oil palm EFB used in this study was obtained from a nearby palm oil mill, Nibong Tebal, Malaysia. The ultimate and proximate analyses of EFB are tabulated in Table 1.

Table 1. The ultimate and proximate analyses of the biomass feedstock.

Proximate analysis (wt%)	EFB
Moisture	7.80
Volatiles	79.34
Ash	4.50
Fixed carbon	8.36
HHV, MJ/kg (dry basis)	15.22
Ultimate analysis (wt%)	
Carbon	43.52
Hydrogen	5.72
Nitrogen	1.20
Sulfur	0.66
Oxygen (diff.)	48.90

The dolomite used in the experiments as the bed material was obtained from a mine located in Damavand Mountain, Iran. Raw dolomite was crushed and sieved to 600–710 μm . The dolomite was calcined at 800 °C for 3 h to remove the carbon and improve the porosity of particles.

The fluidized bed gasifier consisted of a refractory lime tube with internal diameter of 150 mm and height of 700 mm. The reactor was expanded in the freeboard to 270 mm internal diameter and 350 mm height. The ambient air supplied by a 0.75 KW blower was used as the gasifying agent. The feeder was equipped with a frequency variable inverter to control the feeding rates in the range of 6–11 kg/h. The biomass feed rate was varied based on the ER, while the air flow rate was kept constant at 130 L/min. Five type K thermocouples were mounted on the reactor for real-time monitoring of the temperature. The bed temperature was varied from 650 to 1050 °C. The schematic set-up is presented in Figure 1.

Gasification products were passed through a cyclone separator to remove solid particles from the gas. Part of the producer gas was passed through a gas sampling train consisting of a series of bottles partially filled with chilled water and a bottle of silica gel to remove moisture and tar from the gas. The gas samples were collected in Tedlar bags (Cole-Parmer) and analyzed in a gas chromatograph (Agilent technology, 4890) equipped with a thermal conductivity detector (TCD) and a packed column (Carboxene 1000 (4.5 m \times 3.2 mm, 80/100 mesh), Supelco, USA).

2.2. Application of RSM

The 2 independent variables selected for investigation were bed temperature (X_T : 650, 750, and 850 °C) and equivalence ratio (X_{ER} : 0.18, 0.23, and 0.28). CCD was used as a standard model. The optimization was conducted for 8 major responses, namely H₂ (vol.%), CO (vol.%), CH₄ (vol.%), and CO₂ (vol.%) content of the producer gas; HHV (MJ/Nm³); carbon conversion efficiency (%); dry gas yield (Nm³/kg); and cold gas efficiency (%).

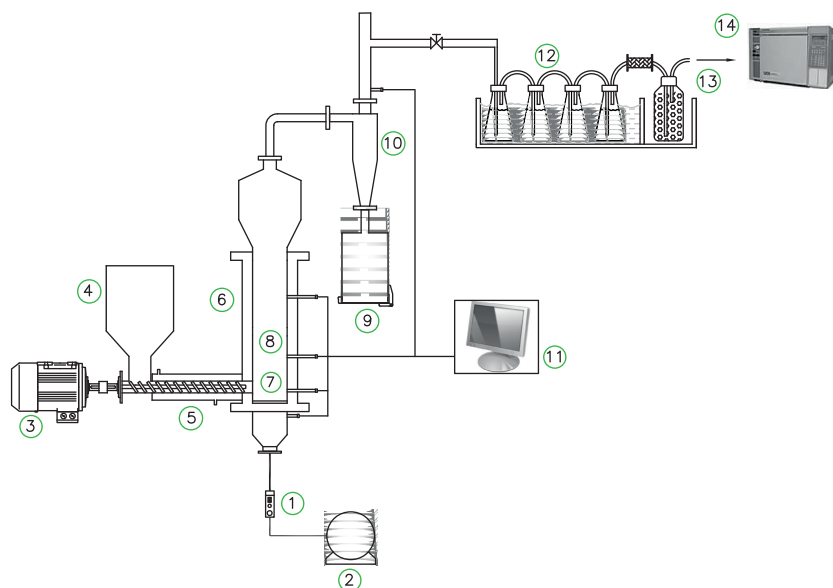


Figure 1. Schematic representation of the pilot scale fluidized bed gasifier: 1. Flow meter; 2. Blower; 3. Variable frequency driver; 4. Feeding hopper; 5. Water cooled screw feeding system; 6. Fluidized bed reactor; 7. Air distributor plate; 8. Bed zone; 9. Ash collector; 10. Cyclone separator; 11. Temperature monitoring unit; 12. Condensers; 13. Silica gel; 14. Gas chromatograph.

3. Results and discussion

3.1. Effect of bed temperature

The effect of bed temperature on the producer gas composition was studied in the range of 650 to 1050 °C with increments of 100 °C, while the ER was fixed at 0.23. Figure 2 illustrates the effect of bed temperature on the producer gas composition. By increasing the bed temperature from 650 to 1050 °C, the H₂ concentration was improved from 12.15% to 16.88% and the CO concentration increased from 14.65% to 18.67%. In contrast, the CO₂ level decreased from 20.59% to 17.45% with increasing temperature. The highest CH₄ concentration was achieved at 650 °C. By increasing the bed temperature, the methane content was decreased from 3.77% to 2.61%. Such variations in the producer gas composition were attributed to the promotion or prevention of the thermodynamic reactions involved in the gasification process (see the *Producer gas composition* section).

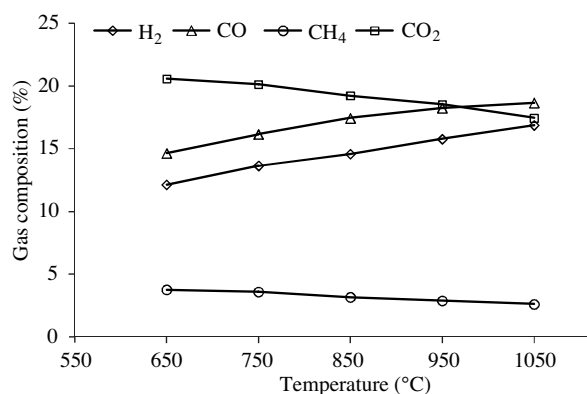


Figure 2. Effect of bed temperature on catalytic gasification outputs of EFB.

3.2. Bed agglomeration studies with calcined dolomite

Bed agglomeration at high temperatures is the main issue in EFB gasification, especially while using silica sand as the bed material (Lahijani and Zainal, 2010). Such an undesired phenomenon originates from the high K_2O (44%) content of EFB, which deteriorates the sintering and agglomeration tendency of the bed material (silica sand) to form low melting K_2O-SiO_2 eutectics (Lahijani and Zainal, 2010). Thus, in this study dolomite was used as an alternative bed material to reduce the sintering tendency of the bed. It has been found that addition of dolomite to the bed material in a fluidized bed biomass gasifier effectively prevents or reduces the agglomeration tendency (Gusta et al., 2009). This ability mostly originates from the presence of Ca and Mg as the dominant components of dolomite (Bhattacharya and Harttig, 2003).

The XRF analysis of the EFB ash and dolomite is shown in Table 2. Use of dolomite as a Ca-rich (34.69%) and Mg-rich (15.06%) mineral causes the formation of anhydrite, i.e. calcium sulfate, which has a melting point of around 1400 °C. Thus, at the fluidized bed temperatures, this compound is not sticky and does not induce agglomeration. In the case of our experiment, it was observed that use of calcined dolomite as the bed material was effective in controlling agglomeration up to 850 °C. Increase in the bed temperature to beyond 850 °C resulted in the growth of the bed particles. However, agglomeration was not severe and the size of agglomerates was not considerable. Figure 3 presents the scanning electron microscopy (SEM) and energy-dispersive X-ray analysis (EDX) of (a) raw and (b) agglomerated dolomite collected from a gasifier at 1050 °C. As presented in the EDX micrographs of the samples, Ca, Mg, O, and C were the major components of the raw dolomite, whereas K, Si, Al, and P were also detected in EDX analysis of the agglomerated dolomite. Presence of these elements further confirms the formation of eutectics, which refers to the high alkali content of EFB. The SEM image of the agglomerated sample clearly represents the formed eutectics on the surface. Due to the bed agglomeration concern at high temperatures, in the optimization experiments the bed temperature was varied from 650 to 850 °C, which was a safe range to prevent sintering and agglomeration of the dolomite particles.

Table 2. Chemical composition of the ash of EFB and dolomite.

Composition (wt%)	Na ₂ O	MgO	Al ₂ O ₃	Si ₂ O	P ₂ O ₅	SO ₃	Cl	K ₂ O	CaO	Fe ₂ O ₃	TiO ₂	MnO	SrO	LOI
Dolomite	0.44	15.06	1.07	2.34	0.02	0.16	-	0.12	34.69	0.61	0.04	0.02	0.02	45.40
EFB ash	0.55	4.80	0.97	27.0	3.60	2.70	5.30	44.0	8.00	3.00	0.08	0.11	0.03	-

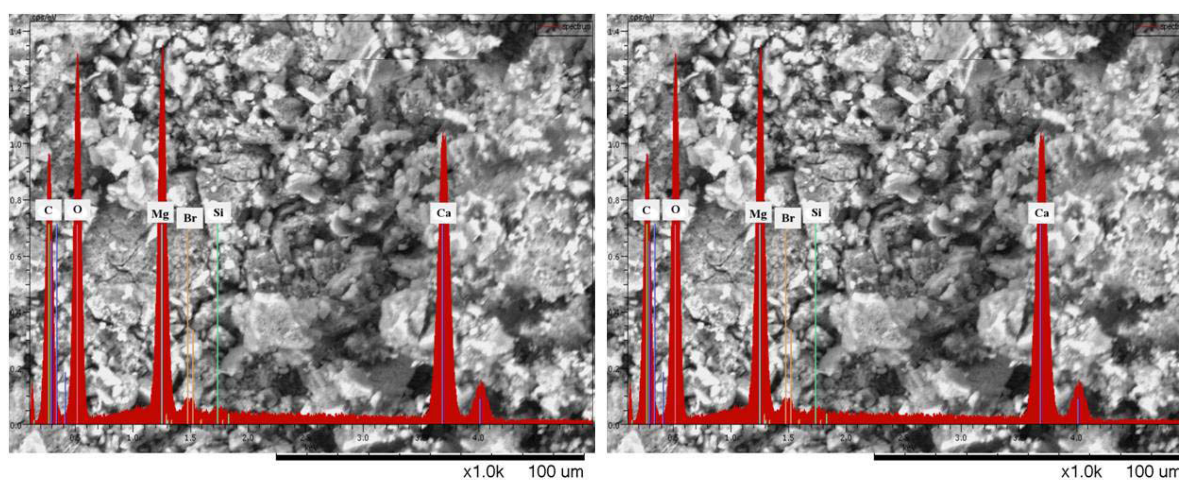


Figure 3. SEM image and EDX micrograph of (a) raw and (b) agglomerated dolomite collected from gasifier at 1050 °C.

3.3. Development of regression model equation

In this study, based on the employed independent variables, CCD designed a set of experiments with 13 runs. The results of the experimental runs are summarized in Figure 4. The relationships between responses and dependent variables were not linear. Therefore, a statistical technique was used to fit the quadratic model to the data.

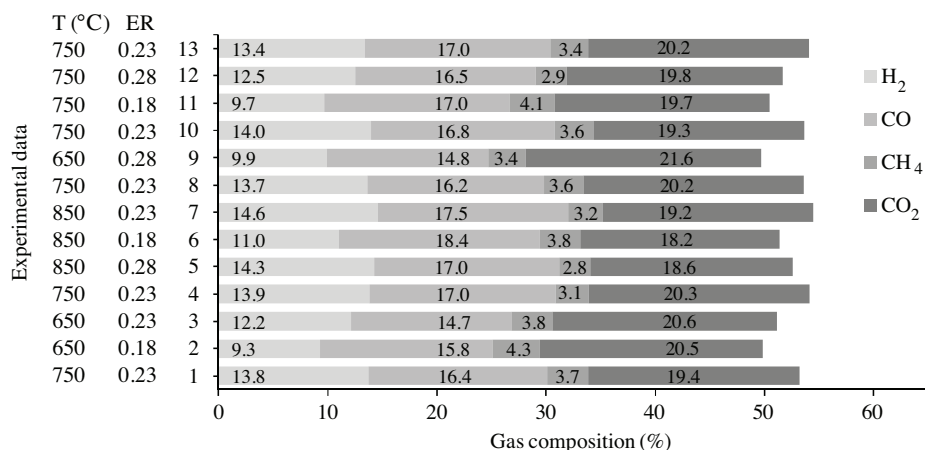


Figure 4. The proposed operation conditions by the software and the experimental results for gasification.

The adequacy of the model for the producer gas quality and gasification performance was justified through analysis of variance (ANOVA). The ANOVA for the quadratic models including the corresponding significant model terms, F-value, individual terms, and lack of fit for all responses is summarized in Table 3.

Table 3. ANOVA for the producer gas concentration and gasification performance indexes.

Response variables	H ₂	CO	CH ₄	CO ₂	Carbon conversion	Heating value	Dry gas yield	Cold gas efficiency
Model	13.67	16.64	3.46	19.87	81.37	5.22	1.66	56.81
R ²	0.9830	0.9153	0.8797	0.8294	0.9831	0.9488	0.9944	0.9897
Adj-R ²	0.9708	0.8547	0.7937	0.7075	0.9711	0.9123	0.9903	0.9823
Std. Dev.	0.32	0.39	0.20	0.48	1.95	0.073	0.025	1012
Mean	12.46	16.56	3.51	19.80	78.45	5.08	1.60	53.41
F-value	80.80	15.12	10.24	6.80	81.54	25.97	246.36	134.13
P-value	< 0.0001	0.0012	0.0040	0.0129	< 0.0001	0.0002	< 0.0001	< 0.0001

The results were fitted to a second-order quadratic model and the coefficients were decoded to real operating variables. The final empirical models in terms of actual factors after elimination of the insignificant terms are shown in Table 4.

3.4. Analysis of response variables

In order to determine the optimum condition for EFB gasification, the pre-described quadratic models were applied to the gasification experimental data. As illustrated in Table 3, correlation confidence (R²) of 89% to 99% was achieved for all responses, which confirmed the suitability of the quadratic models to interpret the experimental results. Although a very high value of R² was not attainable in this study, the pilot scale of the gasification system and the difficulties in data collection may justify the fairly good R² values. From the

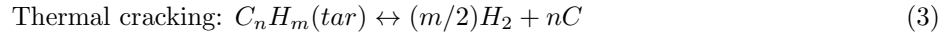
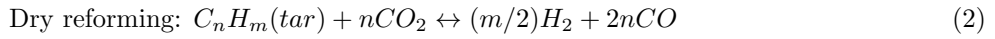
ANOVA results (Table 3) it was inferred that only P-values (Prob > F) less than 0.05 were considered to be significant. Hence, the insignificant statistical terms could be ignored without damaging the model fitting. The lack of fit was also found to be insignificant in all models at 95% confidence level.

Table 4. Empirical models in terms of coded factors.

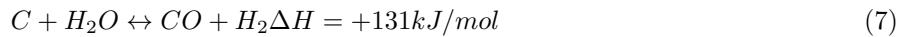
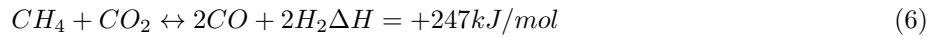
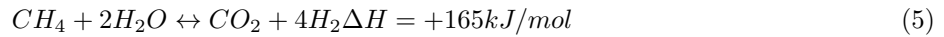
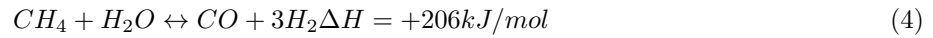
Response	Polynomial equations
Hydrogen	$-40.83 + 9.28E-3 \times T + 374.99 \times ER + 0.13 \times T \times ER - 978.62 \times ER^2$
Carbon monoxide	$-16.61 + 0.09 \times T - 60.11 \times ER + 141.17 \times ER^2$
Methane	$11.51 - 21.63 \times ER + 4.39 \times T^2 + 27.58 \times ER^2$
Carbon dioxide	$18.23 + 63.92 \times ER - 0.04 \times T \times ER - 69.10 \times ER^2$
Carbon conversion	$-187.19 + 0.25 \times T + 1117.77 \times ER + 0.06 \times T \times ER - 1868.41 \times ER^2$
High heating value	$-2.83 + 8.98E-3 \times T + 35.98 \times ER - 103.31 \times ER^2$
Dry gas yield	$-2.44 + 2.08 E-3 \times T + 20.24 \times ER - 37.24 \times ER^2$
Cold gas efficiency	$-157.92 + 0.15 \times T + 1041.02 \times ER + 0.36 \times T \times ER - 2425.59 \times ER^2$

3.5. Producer gas composition

Figure 5(a) shows the 3-dimensional evolution of H₂ with respect to the bed temperature and ER. As thermodynamically predicted, increasing the bed temperature from 650 to 850 °C promoted the hydrogen production from 9.29% to 14.59%. This remarkable increase in the H₂ content of the producer gas could be confidently related to tar cracking. Tar destruction by reforming and cracking reactions (2–4) in the presence of calcined dolomite, which is strongly active at temperatures above 800 °C (Delgado et al., 1996), was the main cause of increased H₂ production (Devi et al., 2005):



Furthermore, the improved H₂ evolution at high temperatures may originate from the highly endothermic methane steam and dry reforming (5–7) (Weerachanchai et al., 2009). The endothermic water–gas reaction (8) that reforms the char can also contribute to the H₂ production at high temperatures:



Meanwhile, H₂ production is affected by ER, which introduces various concentrations of oxygen into the reactor. By increasing the ER from 0.18 to 0.28, the H₂ level of the producer gas initially increased and then gradually declined as depicted in the saddle-type surface of Figure 5(a). The maximum H₂ concentration of 14.59% was obtained at ER of 0.23. Increasing the ER to over 0.23 introduced more air into the system, which improved the oxidation reactions. Thus, the concentrations of H₂ and other combustible gases decreased.

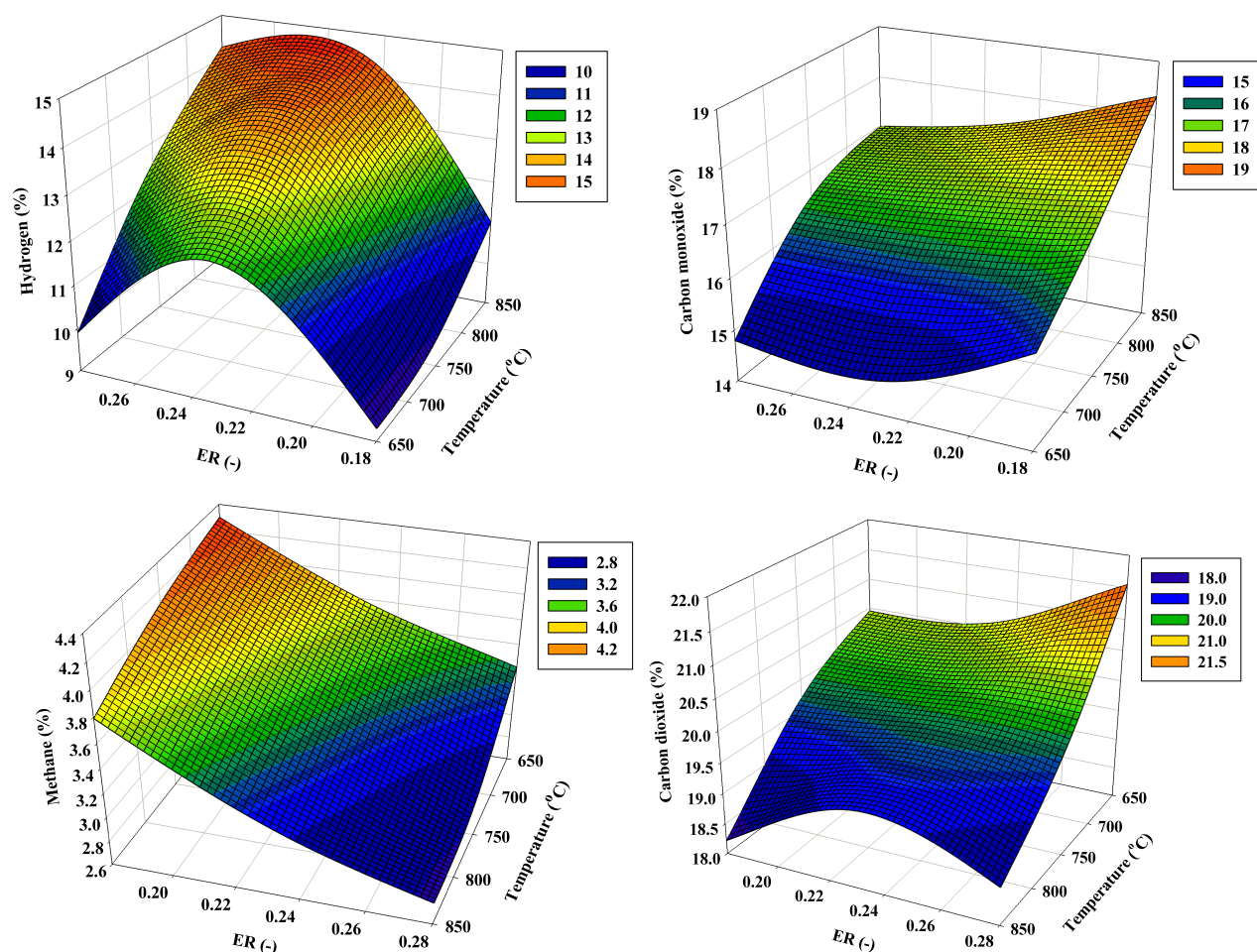


Figure 5. 3D response surface plot indicating the effect of bed temperature and ER on (a) hydrogen, (b) carbon monoxide, (c) methane, and (d) carbon dioxide concentration.

Table 4 shows the regression equation for hydrogen production. The bed temperature (A), ER (B), and the interactions between these 2 variables (AB and B^2) were found to be significant in the developed model. The model F-value of 80.80 and P-value (Prob > F) less than 0.0001 implies that the model is highly significant. The high F-value of temperature (117.21) and ER (72.48) validates that hydrogen content of the producer gas is highly dependent on variations in the bed temperature and ER.

The variation in the CO level of the producer gas with the bed temperature and ER is depicted in Figure 5(b). As the rising ridge surface indicates, the CO concentration gradually increased from 14.65% to 18.35%, while the bed temperature was raised from 650 to 850 °C. Although such an increase in CO level can be achieved through various mechanisms of the steam (5) and dry (7) reforming of methane, water-gas (8), Boudouard (9), and tar cracking (2 and 3) reactions (Lahijani and Zainal, 2010), the catalytic role of dolomite in tar destruction is of utmost importance:



The tar cracking reactions that generate combustible gases, mainly hydrogen and carbon monoxide, are responsible for the increased CO production at high temperatures. In contrast, increase in the ER from 0.18 to

0.28 negatively affected the CO production. As confirmed by other researchers, high ERs promote combustion reactions due to the high level of oxygen introduced into the gasifier. Such a process improves the char burning reaction and CO₂ is generated at the expense of reduced CO production.

The regression equation for CO production (Table 4) and the ANOVA evaluation of the model (Table 3) indicate that, in this case, the bed temperature and ER are the only significant model terms, while any interactions between these parameters were insignificant and can be omitted from the model. The model F-value of 15.12 implies that the model is significant.

Figure 5(c) demonstrates the interaction between the bed temperature and ER on methane production. It was observed that increasing the ER and bed temperature decreased the methane level of the producer gas. The highest methane concentration of 4.30% was achieved at the bed temperature of 650 °C and ER of 0.18. The methane concentration drastically decreased to 2.87% while the bed temperature was increased to 850 °C at ER of 0.28. It is well known that tar cracking at high temperatures can improve methane evolution; however, the generated CH₄ can be consumed through methane dry and steam reforming reactions.

The results obtained from ANOVA of the F-value revealed that only bed temperature (11.59) and ER (38.84) were significant. The model F-value of 10.24 implies that the model is significant.

Figure 5(d) demonstrates the response surface 3D plot for CO₂ production resulting from the interaction between the bed temperature and ER. As depicted in this figure, increasing the bed temperature caused a linear drop in CO₂ concentration, while increase in the ER had a slightly positive effect on CO₂ level. The lowest CO₂ concentration of 18.22% was achieved at the ER of 0.18 and bed temperature of 850 °C. At higher ERs, the high air/fuel ratio promoted combustion reactions and improved char burning, which consequently resulted in enhanced CO₂ production. In contrast, at high bed temperatures, the generated CO₂ was consumed through tar and methane dry reforming and Boudouard reactions and reduced the level of this noncombustible gas in the product gas.

The regression equation of CO₂ concentration shows that its production depends significantly on temperature as individual independent variable and the interactions between temperature and ER. The higher F-value of the bed temperature (31.32) in comparison to ER (1.74) shows that the temperature is a much more significant parameter than ER.

3.6. Gasification performance

Carbon conversion is an important parameter for evaluating the performance of the system. It represents the volumetric percentage of the carbonaceous gas species in the producer gas to the solid carbon in the input biomass:

$$\eta_C = \frac{Y(CO\% + CH_4\% + CO_2\%) \times 12}{22.4 \times C\%} \times 100\% \quad (9)$$

where Y is the dry gas yield (Nm³/kg) and $C\%$ is the mass percentage of carbon in the feed. The variation in carbon conversion efficiency with respect to the bed temperature and ER is presented in Figure 6(a). As expected, at high ERs, the higher amount of oxygen entered into the system enhanced carbon conversion efficiency due to improvement of the oxidation and combustion reactions. High bed temperatures also favored enhanced carbon conversion. At high temperatures, CO₂ was consumed through tar reforming and char gasification reactions to yield more CO. However, increase in the bed temperature was less effective on the carbon conversion efficiency in comparison to ER. The maximum carbon conversion efficiency of 92.88% was achieved at the ER of 0.28 and bed temperature of 850 °C.

The regression equation and ANOVA evaluation of the model showed that the bed temperature (A) and ER (B) and B^2 were significant, while the interactions between the variables were not significant on this response. The higher F-value of ER (373.470) in comparison to the bed temperature (8.26) indicates that ER is more significant on this model term.

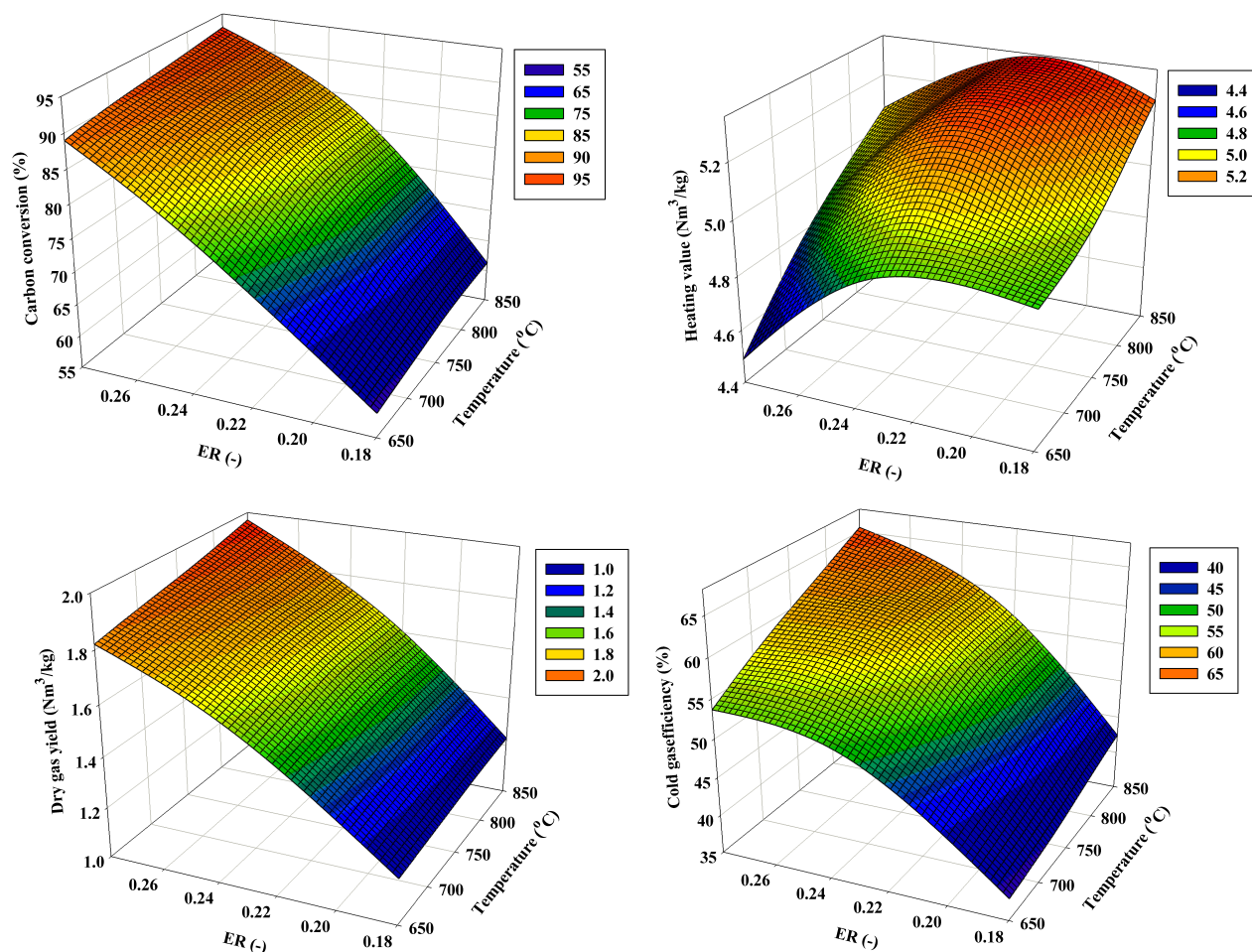


Figure 6. 3D response surface plot indicating the effect of bed temperature and ER on the (a) carbon conversion efficiency, (b) high heating value, (c) dry gas yield, and (d) cold gas efficiency.

Generally, the effectiveness of the gasification process is assessed in terms of the high heating value of the producer gas, which is defined as

$$HHV = (H_2\% \times 30.52 + CO\% \times 30.18 + CH_4\% \times 95) \times 4.1868 \quad (MJ/Nm^3) \quad (10)$$

Figure 6(b) shows the effect of the bed temperature and ER on HHV of the producer gas. As illustrated in this figure, increase in the bed temperature from 650 to 850 °C improved the HHV from 4.49 to 5.33 MJ/m³. High temperatures enhanced the HHV of the producer gas due to the evolution of combustible gases, mainly H₂ and CO. Variation in the HHV with respect to the ER resulted in an optimum (ER = 0.23) at which maximum HHV was achieved. Increase in the ER to beyond 0.23 reduced the energy content of the producer gas due to the reduced concentrations of H₂, CH₄, and CO. Moreover, the low HHV of the producer gas was attributed

to the dilution of the producer gas by the nitrogen provided by the air. Maximum HHV of 5.33 MJ/m^3 was obtained at the bed temperature of $850 \text{ }^\circ\text{C}$ and ER of 0.23. In this case, the independent variables of the bed temperature (A) and ER (B) and B^2 were the significant model terms. The model F-value of 25.97 implies that the model is significant.

Dry gas yield was calculated based on the nitrogen concentration of ash-free biomass. The nitrogen content of the biomass was ignored while calculating the dry gas yield and just N_2 content in air and producer gas were considered in mass balance to obtain dry gas yield (Xiao et al., 2006):

$$Y = \frac{Q_a \times 0.79}{W_b(1 - X_{ash}) \times N_2\%} \quad (\text{Nm}^3/\text{kg}) \quad (11)$$

where Q_a is the flow rate of air (Nm^3/h), W_b is the mass flow rate of biomass (kg/h), X_{ash} is the ash content in the feed, and $\text{N}_2\%$ is the volumetric percentage of nitrogen in the dry producer gas.

Figure 6(c) shows the response surface 3D plot for dry gas yield resulting from the interaction between the bed temperature and ER. As depicted in this figure, increasing the bed temperature caused a slight increase in the gas yield and increase in the ER linearly improved the gas yield. Such improvement in the producer gas yield may have resulted from the promotion of the preliminary pyrolysis rate, progressing of the tar steam reforming, and cracking and development of the char gasification at high temperatures (Pinto et al., 2003). The highest dry gas yield of $1.97 \text{ (Nm}^3/\text{kg)}$ was achieved at the ER of 0.28 and bed temperature of $850 \text{ }^\circ\text{C}$. In this case, the bed temperature (A) and ER (B) and B^2 were the significant model terms. The model F-value of 246.46 implies the model is highly significant.

A comparison between the chemical energy of the producer gas and that of biomass fuel is indicated by cold gas efficiency, which is defined as (Xiao et al., 2006)

$$\eta = \frac{H_g \times Y}{H_b} \times 100 \quad (\%) \quad (12)$$

where the heating value of the producer gas and biomass are represented by H_g (MJ/Nm^3) and H_b (MJ/kg). The achieved results revealed that increasing the bed temperature from 650 to $850 \text{ }^\circ\text{C}$ promoted the cold gas efficiency from 37% to 65%. The regression equation for cold gas efficiency (Table 4) showed that the bed temperature (A), ER (B), and interactions between independent variables (AB and B^2) were significant in the model. The model F-value of 134.13 and P-value ($\text{Prob} > F$) less than 0.0001 imply that the model is highly significant. The high F-values of the bed temperature (81.90) and ER (464.46) validate that the cold gas efficiency of the producer gas is highly dependent on the variations in the bed temperature and ER.

4. Process optimization

Priorities of researchers to obtain a producer gas with the optimum desired properties from the gasification process are somehow dependent on the subsequent applications of the producer gas. In the case of producing biofuel from the producer gas, the ratio between different gases, especially H_2/CO , is of utmost importance. For instance, a stoichiometric ratio of 3:1 H_2/CO is required for ethanol synthesis (Gusta et al., 2009). For the energy production from downstream furnaces, the tar content of the raw producer gas is not a serious issue and the gas should have a higher heating value. In this work, the tar was not a major concern and production of a producer gas with high heating value was considered. Since it was difficult to optimize all responses under

a unique condition, to compromise between the responses, the function of desirability was applied to RSM. As tabulated in Table 5, the experimental conditions with high desirability were selected for verification.

Table 5. Constraints of each variable and response for the numerical optimization.

Conditions	Goal	Lower limit	Upper limit
Temperature	In range	650	850
Equivalence ratio	In range	0.18	0.28
Hydrogen	Maximize	9.29	14.59
Carbon monoxide	Maximize	14.65	18.35
Methane	In range	2.87	4.30
Carbon dioxide	Minimize	18.22	21.55
Carbon conversion	In range	58.70	92.88
Heating value	Maximize	4.49	5.33
Dry gas yield	In range	1.18	1.97
Cold gas efficiency	In range	37.82	65.55

The solution given by the software to meet the proposed criteria in Table 5 was to perform the gasification process at the bed temperature of 850 °C and ER of 0.22, which resulted in 14.59% hydrogen, 17.45% carbon monoxide, 3.31% methane, 18.79% carbon dioxide, carbon conversion efficiency of 76.70%, HHV of 5.39 (MJ/m³), dry gas yield of 1.63 (Nm³/kg), and cold gas efficiency of 57.72%. The predicted desirability was 89.0%.

5. Conclusion

Air gasification of EFB as a common lignocellulosic biomass in Malaysia was studied in a fluidized bed using calcined dolomite. The main objective of this work was to establish optimum operation conditions to obtain a producer gas with improved HHV using a series of experimental runs through statistical analysis. RSM was successfully implemented to predict the effect of the 2 independent variables of bed temperature and ER on the quality of the producer gas. The developed mathematical model reasonably interpreted the experimental data to offer the optimum conditions to obtain a producer gas with improved quality with no agglomeration in the bed.

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Nomenclature

ANOVA	Analysis of variation	Q_a	Flow rate of air (Nm ³ /h)
CCD	Central composite design	R^2	R-squared
EFB	Empty fruit bunch	X_i	Decoded independent process variable
ER	Equivalence ratio	X_j	Decoded independent process variable
HHV	Higher heating value (MJ/Nm ³)	Y	Dry gas yield (Nm ³ /kg)
LHV	Low heating value	β_i	Linear coefficient for the variable
LOI	Loss of ignition (%)	β_{ii}	Quadratic coefficient for the variable
RSM	Response surface method	β_{ij}	Linear model coefficient for the interactions between i and j
SS	Sum of squares	ε	Error
Std. Dev.	Standard deviation	η	Cold gas efficiency (%)
TCD	Thermal conductivity detector	η_c	Carbon conversion (%)

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