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Thermal Plasma Assisted Gasification of Empty Fruit Bunch Biomass using Air-Suction Downdraft Strategy: Effect of Equivalence Ratio and Temperature Profile Characteristic

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ABSTRACT

Plasma gasification is a highly efficient technology in enhancing process rates and gas yield compared to conventional gasification due to its extremely high operational temperatures. However, the operational performance using palm oil biomass in Malaysia as feedstock is still unclear. Hence the present study aims to investigate the effect of equivalence ratio (ER) and temperature on the performance of palm empty fruit bunch biomass (EFB) gasification assisted with plasma reaction process in producing syngas. The performance of produced syngas in terms of the gas composition, yield, lower and higher heating value, cold gas, and carbon conversion efficiency were carefully investigated. The reactor type of air-suction downdraft arrangement has been used in this study. The reactor was then assisted with the DC-thermal arc plasma reaction in the oxidation zone with the maximum power of 9 kW that is applicable to provide a reaction environment temperature of above 1200°C. The result showed that EFB gasification process assisted with plasma produced higher composition of H_2 at lower ER. In contrast, higher CO was produced at higher ER. The extreme high temperature of plasma extent the production of CO by breaking the bonding of CO_2 component either from the produced gas or gasifying agent of air. The characteristic of temperature distribution during the gasification process showed a highly fluctuation profile in the oxidation zones. This is due to the simultaneous exchange between produced gas in the pyrolysis zone and incoming supply of gasifying agent in the reactor inlet. This indicates that the reaction characteristic of plasma gasification is considerably identified with the conventional method. This study is important to identify the optimum operational condition of EFB plasma gasification in terms of the range of ER and temperature distribution characteristic.

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1. Introduction

The extensive utilization of fossil fuels during the last few decades has not only resulted in tremendous climate change but also caused various health and environmental issues. For instance, 41% of the current global electricity demand is directly fulfilled by coal fired power plants which is detrimental to the environment. The damage caused by coal industry can be minimized by using renewable energy [1]. However, renewable energy from wind and solar poses a few significant limitations, including geographic restrictions, reliance on weather, and stochastic and inconsistent power supplies. Biomass is considered as a viable alternative and feasible option to address the problems due to its independence from the effects of the weather, as well as its large deposit and wide dispersion. Presently, biomass accounts for more than 70% of global renewable power and has been established as an essential component of the world's energy resources. It is predicted that biomass can achieve up to 25% of the world's energy needs [2].

Malaysia's palm oil sector is currently generating approximately 50 million tonnes to 100 million tonnes of dry palm oil biomass per year until 2020, as the country is one of the world's largest oil palms planted regions after Indonesia and Thailand [3,4]. The produced biomass from oil palm processing mills through the extraction of fresh fruit bunch (FFB) is typically comprised of empty fruit bunch (EFB) which account for 22%, palm kernel shell (PKS) 5.5%, mesocarp fibres 13.5%, and palm oil mill effluent (POME) [3]. The average quantity of oil palm biomass obtainability in Malaysia is estimated to be 22.42, 7.13 and 71.34 million tonnes of EFB, PKS and POME respectively from 2017 to 2019 according to the FFB outcome figures reported by Malaysia Palm Oil Board (MPOB). Malaysia is thus can possibly employ the biomass to generate value-added goods due to the abundance quantity of annual oil palm biomass production [5].

In contrast to conventional fossil fuel burning, biomass gasification is regarded as a potential renewable process capable of producing flammable syngas for energy production as well as beneficial chemical products [6]. Biomass gasification also proposes highly competent, established, and cost-effective methods of generating low-carbon green hydrogen energy source in the recent time [7]. The gasification process involved a conversion of biomass into a gaseous product known as producer gas or synthesis gas (syngas) which principally contained CO, H_2, CH_4 and CO_2 and other hydrocarbon species. Biomass typically contained cellulose, hemicellulose, lignin, and other components [8]. The high content of hemicellulose and cellulose/lignin ratio is principally capable of generating a high amount of syngas [9]. Thus, gasification process using an appropriate selection of biomass can potentially produce high quality syngas.

The attention on plasma gasification has recently received increasing consideration as an ecologically friendly and effective method to transform the carbon-based components such as municipal solid waste (MSW), plastic tires, and biomass into syngas [10]. Plasma gasification of biomass is a promising technology as an alternative method to the conventional biomass gasification technologies due to it elevated operational temperature (up to 5000^{o}C) and burning rate, thus enhancing the gasification process rates and gas yield [11-13]. In addition, Gasification of biomass with plasma elements also increased the reaction of tar cracking and hence totally extinguish tars under high temperature plasma which led to low tar content in the produced syngas [12]. This indicates that the syngas produced using plasma gasification method is possibly applicable to be directly implemented in internal combustion engine and solid oxide fuel cell (SOFC) with no requirement on extra tar elimination procedures [10].

A few studies on biomass gasification which uses plasma elements in their reactor have been previously conducted. Guo *et al.,* [14] uses a small-scale oxygen-enriched entrained flow biomass gasifier containing a non-thermal arc plasma torch. The influences of oxygen intensity on the gasification process using rice husk powder biomass were investigated. The results reported that increasing the intensity of oxygen as gasifying agent caused the enhancement of cold gas efficiency, carbon conversion efficiency and H_2, CO yield [14]. Vecten *et al.,* [15] reported on the conversion of biomass into combustible gas in a microwave-induced plasma reactor using pure steam as the plasma working gas. The results found that the optimum output was achieved at the highest microwave power of 6 kW with CCE over 98%, The syngas produce also high in caloric value which ranged 10.5 – 12 MJ/Nm^3 due to high hydrogen content which exceeding 60% by volume [15]. Tamošiūnas *et al.,* [13] studied biomass (wood pellets) gasification using direct current (DC) thermal arc plasma at atmospheric pressure. Steam was utilized as a gasifying agent and a plasma-forming gas. The study reported that the produced syngas contained high concentrations of H_2 (43.86 vol.%) and CO (30.93vol.%) and hence high calorific value of 10.23 MJ/Nm^3. The study also claimed that the production of 1kg of syngas required 1.78kWh of electric energy input [13].

To the best author knowledge, there is no specific study on plasma gasification using palm biomass as a feedstock. Hence, the present study is intended to perform an analysis of thermal arc plasma gasification using pelletized EFB as a feedstock.

2. Methodology

2.1 Feedstock Preparation

The present study utilized the empty fruit Bunches (EFB) biomass, as a feed material. The EFB feedstocks was obtained from the DST Technology Company (Bayan Lepas, Penang). The biomass pellets were cylindrical in shape, with dimensions ranging from 15mm to 25 mm in length and 6 mm to 7 mm in diameter as shown in Figure 1. The biomass pellets were made from palm oil trees. The samples of feedstock were then randomly picked and characterized using proximate and ultimate analysis in Engine Laboratory of Universiti Sains Malaysia, USM. The properties of EFB were determined using proximate and ultimate analysis through the thermogravimetric analysis (TGA) and CHNSO elemental analyser as depited in Table 1. The high value of volatile matter content is an indication of high decomposition rate of carbon material. High Carbon, C element also indicates that EFB can potentially produce high amount of combustible gas component in syngas.

Fig. 1. Pelletize empty fruit bunch (EFB)

Table 1
EFB properties through proximate and ultimate analysis

Proximate analysis (wt%)		Ultimate analysis (wt%)	
Moisture Content, MC	8.683	Carbon, C	43.61
Volatile Matter, VM	70.663	Hydrogen, H	9.88
Fixed Carbon, FC	17.827	Nitrogen, N	0.8
Ash Content, AC	2.827	Sulphur, S	0.67
		Others	45.04

Sample weight (mg)	1.645
HHV (J/g)	17219

2.2 Experimental Apparatus and Procedure

The present paper used equipment setup as shown in Figure 2. The setup arrangement was principally contained a fixed bed plasma gasifier, the gas delivery system to supply gasification agent which in this case is air and work gas of compressed air for plasma torch, a cyclone and condensation unit. The complete arrangement system also comprises of a flaring unit and cleaning unit for gas sampling purposes. The plasma gasification reactor was built with cylindrical shape and attributed a total height and internal diameter of 744 mm and 108.2 mm respectively. The internal wall of reactor was also installed with 5 K-type thermocouples to measure the temperature of each zone during gasification process including drying zone, pyrolysis zone, reaction/oxidation zone and reduction zone. The reactor was also attached with the DC plasma torch generated via the gas stream of compressed air which located at reaction zone and operated power range of 0 to 9kW.

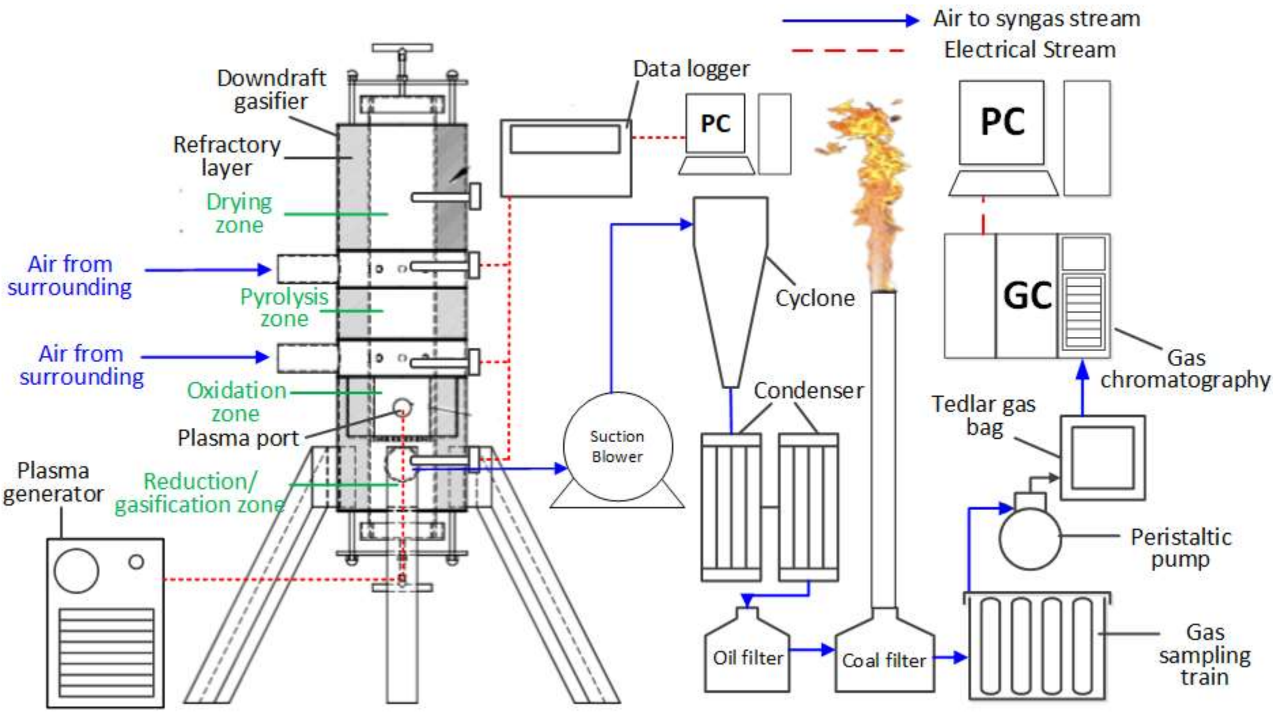

Fig. 2. Experimental apparatus and setup of thermal plasma assisted air-suction downdraft gasifier

The stages of experimental work were as follows: First, the transporter gas of compressed air was inserted into the electrode region of plasma torch with a stream rate of 1.14 Nm^3/h to conserve the consistency of the plasma discharge and the pure inert environment. Next, the DC plasma reactor power input was set to achieve the corresponding temperature of above 1000^oC in the plasma zone which is 9 kW. The feedstock with weight of 1 kg was fed into gasification bed of reactor as the temperature of reaction zone achieved 100-200°C. The surrounding air was suctioned using suction blower into the reactor and used as gasification agent. The produced syngas during the gasification process was then channelled into the cyclone unit and condenser. The thermocouple was used to measure the temperature of the reaction zone. The syngas flow rate was measured by a float-type flowmeter (FVA Trogflux, Mecon).

The produced syngas was then collected through the sampling unit which consisted of a series of impingers glass bottles. The impinger bottles were partially filled with cold water. A Tedlar gas sampling bags (Cole-Parmer) was used to collect the produced syngas that is free from char and ash for the purpose of gas composition analysis. The composition of syngas which comprise of H_2, CO, CO_2 and CH_4 were analysed using gas chromatography, GC (Agilent technology, 4890) which installed with a thermal conductivity detector (TCD) and a capillary packed column of Carboxene 1000 (15 ft 1/8inches, 80/100 mesh), Supelco, USA to distinct each component of gas.

2.3 Quantitative Analysis

The equivalent ratio, ER is calculated using the actual value of air to the feedstock ratio by the stoichiometric value of air to the feedstock ratio as formulated in Eq. (1). The value of stoichiometric air is calculated using the ultimate analysis data of material in Table 1.

$$\text{Equivalent Ratio, ER}=\frac{(\frac{\text{Air}}{\text{Fuel}})_{\text{actual}}}{(\frac{\text{Air}}{\text{Fuel}})_{\text{stoichiometric}}} \tag{1}$$

where AF_{actual} is defined as actual air-fuel ratio, which equivalent to the flowrate of oxidiser divided with the amount of feedstock. $AF_{stoichiometric}$ is defined as the quantity of air require to completely combust the feedstock divided with the quantity of feedstock. The syngas yield is the amount of produced gas which emitted at the outlet of the reactor and formulated as in Eq. (2):

$$Y_{gas}=\frac{V_{gas}}{Mass_{Feedstock}} \tag{2}$$

where V_{gas} is define as the flow rate of the output gas which expressed as the flow rate of dry gas in volumetric base of m^3/h. Whereas $Mass_{Feedstock}$ is defined as the feed rate of feedstock in kg/h. The syngas yield also can be defined in mass basis formulation as in Eq. (3)

$$Y_{gas}=\frac{\dot{m}_{gas}}{\dot{m}_{Feedstock}} \tag{3}$$

where $\dot{m}_{gas}$ and $\dot{m}_{Feedstock}$ is define as mass flow rate of syngas at the reactor outlet and feedstock at the feeder inlet in kg/s respectively. The lower heating value, LHV and higher heating value, HHV is the amount of heat energy that contained in the produced syngas. The unit for both value is MJ/m^3 and calculated as in the Eq. (4) and Eq. (5).

$$\text{LHV}=[12.622(\text{CO})+10.788(\text{H}_2)+35.814(\text{CH}_4)]\times 1/100 \tag{4}$$

$$\text{HHV}= 12.622(\text{CO})+12.769(\text{H}_2)+39.781(\text{CH}_4) \tag{5}$$

where $H_2/100$, $CO/100$ *and* $CH_4/100$ were the constituent of gaseous component in produced syngas. The cold gas efficiency (CGE) and the carbon conversion efficiency (CCE) were another parameter that is vital for the measurement of the gasification process performance. The CGE value is the efficiency ratio of the energy contained in the produced gas to the energy of the feedstock which formulated as in Eq. (6).

$$\text{Cold Gas Efficiency, CGE}=\left(\frac{\gamma_{gas}(HHV)_{gas}}{HHV_{feedstock}}\right)\% \quad (6)$$

where HHV is the higher heating value of the produced syngas, γ_{gas} is define as gas yield with the unit of m^3/kg and $HHV_{feedstock}$ is the higher heating value of the feedstock. The CGE value also can be express by considering the input power from the plasma element. By considering plasma input power and substituting Eq. (3), Eq. (6) become

$$\text{Cold Gas Efficiency, CGE}=\left(\frac{\dot{m}_{syngas}\cdot(LHV)_{gas}}{\dot{m}_{Feedstock}\cdot(LHV)_{feedstock}+\dot{W}}\right)\% \quad (7)$$

where LHV syngas and LHV feed are the lower heating value (kJ/kg) of syngas and feedstock respectively. W is the electrical power (kW) operated for creation of plasma. The carbon conversion efficiency (CCE) is an efficiency measurement for the ratio of carbon element that contain in the syngas to the carbon material in the feedstock. The CCE value by considering molecular weight is calculated using the Eq. (8)

$$\text{Carbon Coversion Efficiency, CCE}=\left(\frac{\dot{m}_{syngas}\cdot Y_i}{\dot{m}_{Feedstock}\cdot Y_c}\right)\%=\left(\frac{\dot{m}_{syngas}(YCO_2\frac{12}{44}+YCO\frac{12}{28}+YCH_4\frac{12}{16})}{\dot{m}_{Feedstock}\cdot Y_c}\right)\% \quad (8)$$

where yi is the mass fraction of species i in the producer gas. Yc is the mass percentage of carbon in the feedstock which is measured via the ultimate analysis. Eq. (8) can be simplified by substituting Eq. (3) to become

$$\text{Carbon Coversion Efficiency, CCE}=\left(\frac{12\times\gamma_{gas}(CO\%+CO_2\%+CH_4\%)}{22.4(C\%)}\right)\% \quad (9)$$

$$\text{Carbon Coversion Efficiency, CCE}=\left(\frac{Carbon_{produced}}{Carbon_{supplied}}\right)\% \quad (10)$$

where $Carbon_{produced}$ is defined as the multiplication of produced syngas yield with the volume percentage of the carbon-based gases component in the syngas including CO, CO_2 and CH_4. Whereas $Carbon_{supplied}$ is the amount of carbon material that contain in the feedstock.

3. Results
3.1 Effect of Equivalence Ratio

The present section describes the results attained from the experiment of EFB pellet biomass gasification plasma reactor. Figure 3 shows the effect of equivalence ratio on the output of syngas via gasification process. The primary component of produced gases was H_2 and CO with minor amounts of CO_2 and CH_4. There are also other lighter hydrocarbon traces that were not displayed in the result. The results clearly indicate that lower region of ER values promote higher production of

H_2 specifically at ER of 0.18 and 0.27 with the value of 8.59 and 10.3 volume percentage (vol. %) respectively. The production of H_2 was then decreased at higher ER of 0.36, 0.42 and 0.46 with the value of 6.77, 6.01 and 6.03 volume percentage (vol. %) respectively. The decrement can be clarified by the point that extra concentration of oxygen is supplied to the plasma gasifier at higher ER value which leads to a higher degree of combustion reactions as in Eq. (11) and Eq. (12).

$$CO+\frac{1}{2}O_2 \rightarrow CO_2 \Delta H^{\circ}_{298}=-284\,\frac{MJ}{kmol} \tag{11}$$

$$H_2+\frac{1}{2}O_2 \rightarrow H_2O \Delta H^{\circ}_{298}=-484\,\frac{MJ}{kmol} \tag{12}$$

The extreme combustion to completion products produced H_2O and thus reduced the radical component of H_2. The results agree with the previous study which also reported on the influence of ER on the production of syngas composition using plasma gasification [16]. However, the trend of CO is contradicted with H_2 as CO is increase with the increase in ER. This seems that higher ER at certain stages promote more chemical heat by combustion for gasification, which is favorable to syngas production [17]. The endothermic process occurs in gasification zone as the heat from combustion zone increases due to the increasing of ER (increase in air supply) hence promote the reaction of water gas and Boudouard reaction as in Eq. (13) and Eq. (14) to produce higher CO. The further increase in ER caused more combustion reaction to occur which consuming CO in a first place for exothermic process in combustion zone. Thus, CO is reduced when the ER further increases to the value of 0.46.

$$C + H_2O \rightarrow CO + H_2,\ \triangle H^0 = 131.4\ kJmol^{-1} \tag{13}$$

$$C + CO_2 \rightarrow 2\,CO,\ \triangle H^0 = 172.6\ kJmol^{-1} \tag{14}$$

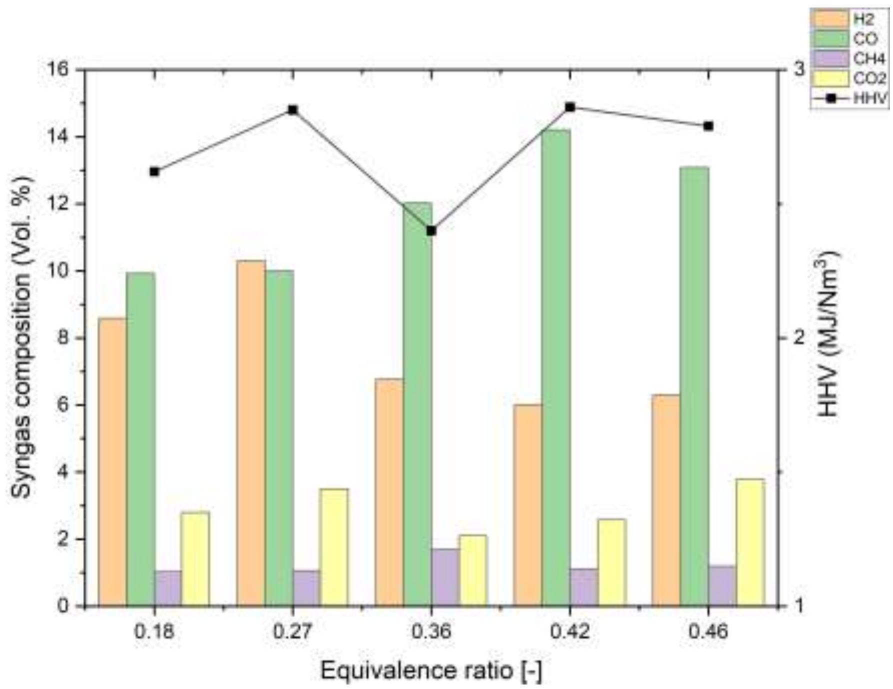

Fig. 3. Syngas composition and HHV against ER for EFB biomass plasma assisted gasification

A typical gasification process produced an increasing profile of CO_2 with the increases of ER. This is due to the extent of oxidation process which provides higher oxygen content and promotes complete formation of CO to CO_2 [18]. These profiles can be observed at ER of 0.18 to 0.27. However, the CO_2 content was reduced when ER is increased from 0.27 to 0.36. The reduction of CO_2 was relatively due to the reaction which is more favorable to the production of CO as explained previously. Higher ER somewhat promotes chemical heat which caused the endothermic reaction of R7 and R9 to take place and produce CO. Further increase in air supply means higher ER at 0.42 and 0.46 which extent the oxidation reaction hence increases the production of CO_2 via the formation CO with O_2 through the reaction of R6. This trend also agrees with some previous studies [19,20].

The performance of plasma gasification also can be measured using cold gas efficiency (CGE) and carbon conversion efficiency (CCE). CGE is defined as the ratio of syngas produced energy to feedstock input energy. Whereas CCE is the ratio of the carbon element in the syngas to carbon element in the feedstock. Both indices can be expressed as in Eq. (7) and Eq. (8).

Where $\dot{m}$ syngas and $\dot{m}$ feed are the mass flow rates (kg/s) of syngas and feedstock respectively. LHV syngas and LHV feed are the lower heating value (kJ/kg) of syngas and feedstock respectively. $\dot{W}$ is electrical power (kW) operated for creation of plasma. The yi is the mass fraction of species i in the producer gas. Yc is the mass percentage of carbon in the feedstock which is measured via the ultimate analysis. Figure 4 showed the results of CGE and CCE against ER. The results showed that CGE is relatively increased with the increased of H_2 and CO production as ER increased from 0.15 to 0.35. CGE was reduced as ER further increased from 0.35 to 0.50. This seems to be caused by the reduction amount of H_2 in the production of syngas. The reduction of H_2 relatively reduces the syngas mass flow rate and hence the HHV, thus reducing efficiency. Even though the amount of CO is increased beyond the ER of 0.35, the high reduction of H_2 seems dominantly affected the overall efficiency of the cold gas. The results also showed that CCE was continuously increasing as the ER increases. CCE is the indication of conversion of carbon element to syngas specifically for component of CO, CH_4 and CO_2. Hence, this is not surprising as the production of CO was keep increasing as the ER increases [21].

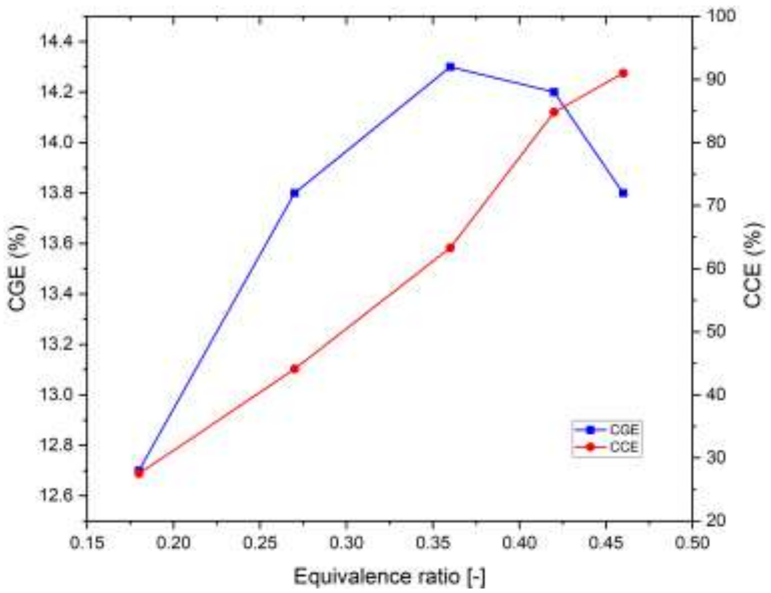

Fig. 4. CGE and CCE value against ER for EFB biomass plasma assisted gasification

Figure 5 showed the syngas yield was continuously increasing as ER increased. The syngas yield was increased from 1.62 to 4.1 with the increase ER from 0.18 to 0.46. The results agreed with Meng *et al.,* [22] which also reported a continuous increase in gas yield with the increase of ER. Meng *et al.,* [22] indicates that the increase in gas yield was mainly contributed by the increase in gasifying agent of air resulted from the increase in ER. Awais *et al.,* [23] also reported a similar trend of increase gas yield with the increase in ER. Awais *et al.,* [23] also highlighted that the high amount of available oxygen component due to high ER contributes to the high production of gas.

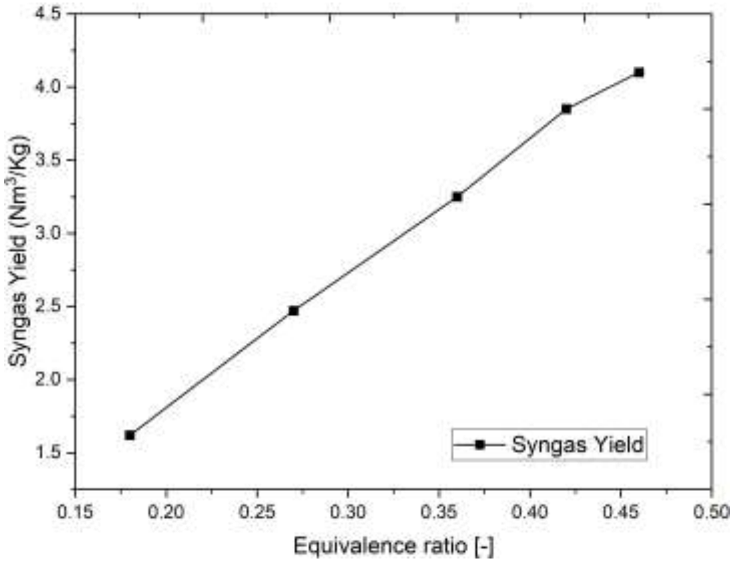

Fig. 5. Syngas yield against ER for EFB biomass plasma assisted gasification

3.2 Temperature Distribution

Figure 6 shows the distribution of temperature in the plasma gasification reactor for different zones of pyrolysis, oxidation, and reduction or gasification zone at the condition of ER of 0.18, 0.27, 0.36 and 0.42 respectively. The overall trend depicted that the oxidation or combustion zone attribute higher distribution of temperature followed by temperature at gasification or reduction zone and pyrolysis zone. The trend was a typical trend in gasification reactors in which the higher temperature certainly occurs at the zone close to plasma flame position and it agrees with the one reported by previous research. The temperature distribution in all zones also typically exhibited an oscillations behavior. This can be explained through the flow condition inside the reactor during the gasification process which attributes an alternate flow between gasifying air supply at the intake and the flow of produced syngas. The alternate cycle was initiated first from the air flow which assists the plasma combustion and partial oxidation of the feedstock. The produced syngas from the partial oxidation process is then moved upward into the pyrolysis zone due to the buoyancy effect as high temperature of heated molecule attribute lower density and lighter weight than surrounding air. The high temperature of syngas in this zone was then lost heat through the pyrolysis reaction of the feedstock due to the energy release for exothermic process. The cooled syngas which attributes high density molecule will lose buoyancy and hence slump down back to the oxidation and gasification zone which hindered the continuity of intake air flow as well as the combustion process [24,25]. This will lead to the reduction of produced syngas. The gasification process will then naturally be self-regulated by allowing more intake of air to take place as again to increase the combustion reaction and temperature. Then the new cycle started and repeated which caused the oscillation on the distribution of temperature to occur.

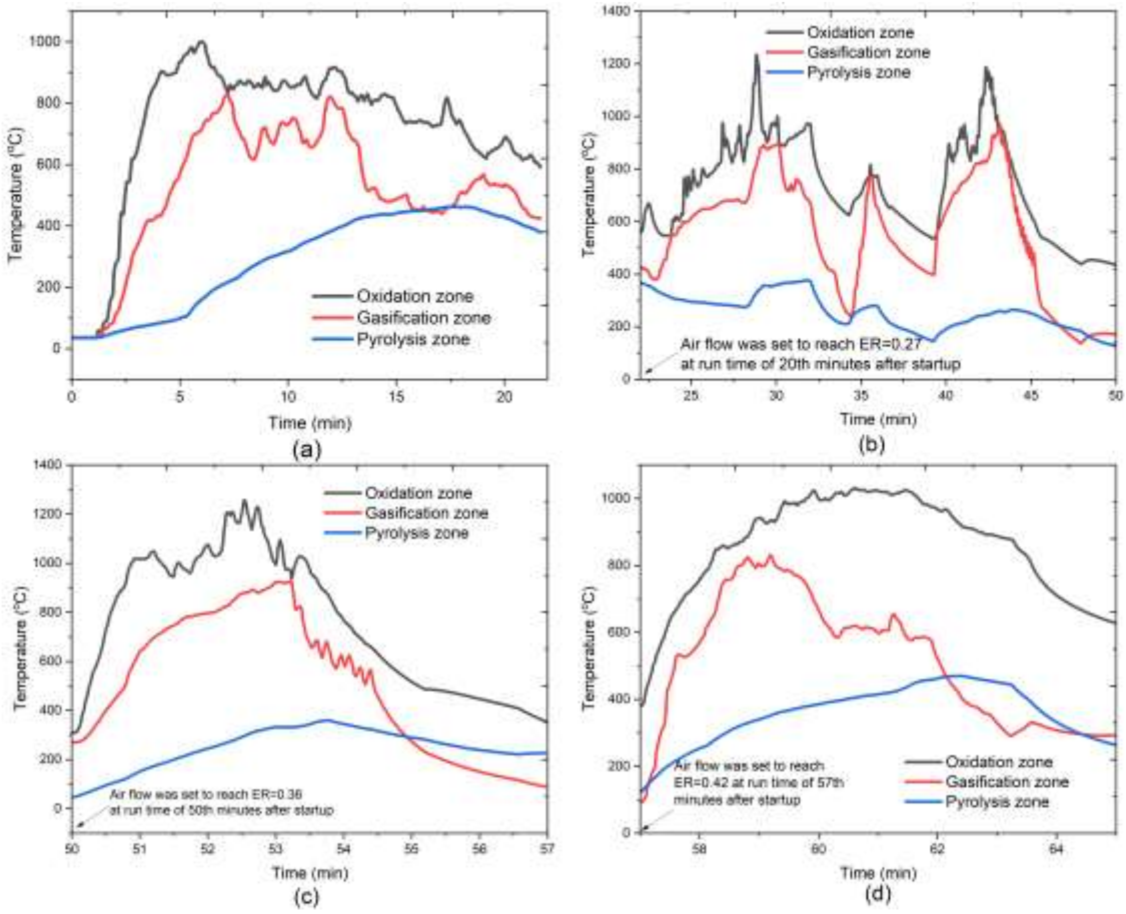

Fig. 6. Temperature distribution against time for EFB biomass plasma assisted gasification at ER of (a) 018 (b) 0.27 (c) 0.36 and (d) 0.42

The distribution of the temperature at reduction or gasification zone was typically lower than oxidation zone. The temperature at this zone was not directly influenced by plasma flame hence not an exothermic process but rather an endothermic process which heat energy being absorbed to release the radical component of H_2 and CO through the water gas and Boudouard reactions. The absorbed heat was thus reducing the temperature and resulted in a lower distribution of temperature as compared to oxidation zone.

The distribution of temperature in oxidation zone at ER 0.27 and 0.36 attributed a significant isolated high peak at certain time as shown in Figure 6(b) and Figure 6(c). The complimentary of the increase of air at higher ER and the domination of partial oxidation process rather than complete combustion at this condition caused the exothermic and endothermic process were alternately experienced sudden increase and decrease at certain time hence produced the isolated peak. The distribution of temperature at ER 0.42 attributed a smooth profile without sudden high peak at certain time especially for oxidation zone. The high amount of supply air caused the reaction to be more prone to complete combustion. Hence the heat absorbed process by endothermic reaction is reduced resulted to the consistency process of exothermic reaction without reduction of produced heat as well as temperature throughout the duration of process.

The result of temperature is also presented by taking the average value across the reactor height as shown in Figure 7. This analysis is crucial as to provide an insight of the vertical profile of temperature across all the involved reaction zone including drying, pyrolysis, oxidation, and reduction within the reactor. The maximum temperature was relatively attributed at the plasma flame region and close to bed surface of feedstock which indicate the occurrence of oxidation process of char and volatiles matter via the O_2 element in air.

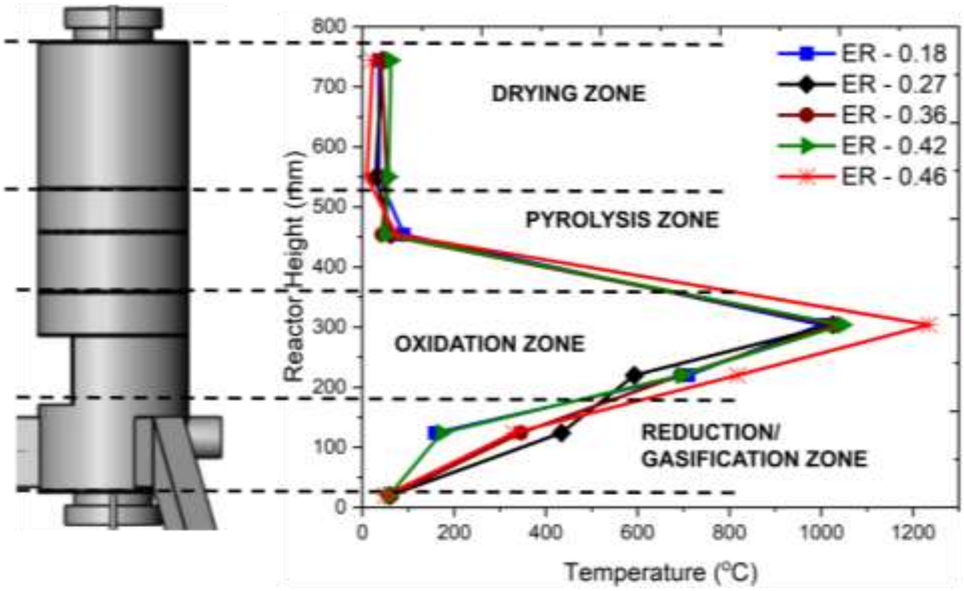

Fig. 7. Reactor height against temperature distribution for EFB biomass plasma assisted gasification

The oxidation process of char through the reaction of R4 to R6 to produced CO and CO_2 were relatively an exothermic process which resulted in the heat energy release to promote the gasification process and hence increase the temperature at that region. It is observed that temperature in pyrolysis zone was lower as the distance of feedstock from the heat source of plasma flame is increase. In addition, the temperature in pyrolysis zone was also experiences a transition of temperature from 200°C to 800°C at reactor height between 400 mm to 500 mm which indicate the condition of before and after exceeding the minimum heat energy that require to removed moisture from the feedstock. The lower temperature at reduction or gasification seems to be due to the dual factor of the distance from heat source and the endothermic process to generate the producer gas. It is notable that temperature will be lower as the distance was getting further from the heat source. The temperature was then further reduced as the endothermic process which absorbed heat rather than released heat occurred via the Boudouard and water gas reaction to produce radical components of CO and H_2. The result also showed that the maximum oxidation temperature was recorded at ER 0.46. This condition is straightforward as the increase in temperature was relatively due to the increase of the amount of air supply which provide a medium that accelerating the char and volatile oxidation process and hence release an extensive amount of heat through the exothermic process.

4. Conclusions

The present study investigates the effect of ER on the performance of thermal plasma biomass gasification using air-suction downdraft reactor in producing high quality of syngas. The temperature distribution characteristic was also critically analysed and thoroughly discussed to gained insight of biomass plasma gasification process reaction behaviour. The results found that the produced syngas exhibited an insignificant profile of HHV value as ER increase. This indicate that the amount of combustible gas in syngas is slightly comparable from lower to higher ER value. This is due to the balancing amount of combustible component in syngas between H_2 and CO as the ER increase. The results imply that lower CO and H_2 is counterbalance with higher H_2 and CO at lower and higher ER respectively. This caused the calorific value in terms of HHV of syngas is comparable at any range of ER. The temperature distribution characteristic showed that the higher temperature was typically in oxidation zone followed by gasification or reduction zone and pyrolysis zone. The temperature distribution is observed to significantly exhibited oscillation profile in oxidation and reduction zone. The simultaneous change between hot gas and cold gas in oxidation zone and pyrolysis zone is most probably influenced the oscillation profile. The reduction of temperature by endothermic process in reduction zone also become a primary factor that caused the temperature fluctuation to occur. This temperature profile characteristic also has been reported by previous study which using non-plasma type of reactor [25]. This indicate that plasma gasification reaction attributes an identified temperature characteristic with conventional reactor.

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