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Effect of Equivalence Ratio on EFB Pellet Gasification Characteristic using Thermal Arc Plasma Suction Downdraft Gasifier

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ABSTRACT

The present study investigated the performance of thermal arch plasma suction downdraft gasification which utilizing pelletized empty fruit bunch as a feedstock in producing syngas with high thermochemical conversion efficiency. Gasifying medium of air was used in this system. Syngas produced was evaluated and measured in terms of gas composition, carbon conversion efficiency, cold gas efficiency, syngas yield and calorific value. The effect of different equivalence ratio ranged from 0.18 to 0.46 was also evaluated. The results reported that syngas produced contained higher CO of 14.2 vol% at higher equivalent ratio, 0.42. In contrast to H_2 content, higher composition of 9.92 vol% was produced at lower equivalent ratio, 0.18. HHV and CGE value was higher at equivalent ratio of 0.36 which correspond to the balanced constituent of CO, H_2 and CH_4 at this condition. CCE and syngas yield was maximum at higher equivalent ratio of 0.46 due to higher production of CO from carbon elements. The results of the present study provided a useful data and guideline of equivalent ratio range for operational of plasma downdraft reactor.

1. Introduction

The implementation of energy efficiency, and the development of renewable energy due to the shortage of energy and the worsening of environmental pollution from fossil fuel combustion has become an urgent necessity for the social-economic growth and sustainable development [1,2]. As Malaysia is one of the largest producers in the palm oil industry, the vast quantity of palm oil biomass has been viewed as a potential source of renewable energy [3,4]. Nearly 70% of the fresh fruit bunches in the palm oil refining process, are converted into biomass and waste residues [5]. Each tonne of fresh fruit bunches processed in a typical crude palm oil (CPO) mill produces approximately

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20-22% CPO and generates different type of biomass including EFB, fibers and palm shells with shared percentages of 23-25 %,13-15 %, and 5-6 % respectively.

In contrast to the conventional combustion of fossil fuels, biomass gasification is recognized as a potential renewable fuel conversion technology to produce combustible syngas fuel for application in power generation as well as valuable chemical products [6]. Renewable energy which using bio-based material is also known as green methods is interesting due to it environmentally friendly and low-cost aspect [7]. Syngas, or hydrogen which extracted from synthetic gas, is a raw material that is used in the generation of power, fuel, and compounds (methanol, dimethyl ether, and etc.), hence reduced the dependency on fossil fuel [8]. Plasma gasification is one of the potential technologies that appears to be promising for biomass fuel conversion method due to several advantages. These advantages include a high thermal energy density which leads to smaller reactor measures and results in lower thermal losses, high efficiency of reactor temperature, the potential to operate independently of the environmental gases such as air, inert gases, water steam, etc., a reduction in the emission of polluting gases and a reduction in the volume of treated feedstock [9]. Thus, plasma gasification demonstrated greater energy and material resource savings which exhibit greater benefits to the environment [10].

Previous studies reported that, biomass gasification using a plasma reactor was achieved through a radio frequency (RF) induction plasma, a microwave (MW) plasma, an alternating current (AC) plasma, and a direct current (DC) plasma [11]. Li *et al.,* [12] studied plasma gasification for dried floor and dried rice at a high power of 35kW. The range of PER (0.08–0.53) was studied and indicated that the syngas reaches the peak at PER = 0.25 with corresponding concentrations of 26.6% CO and 10.0% H^2. Nestor *et al.,* [13] carried out the effects of plasma and reactor temperatures on integrated plasma gasification combined cycle (IPGCC) performance. The best thermodynamic performance (32.49 % efficiency) was achieved at a low reactor temperature (2000^oC) and a high plasma temperature (5000^oC) because of a decrease in torch power consumption. Under these conditions, the IPGCC power plant was able to generate 56 MW while processing 900 t/day. Vineet *et al.,* [14] stated that due to the extremely high enthalpy of the plasma treatment, a high level of product conversion and safety can be achieved. Plasma gasification can be a cost-effective and eco-friendly alternative for producing syngas, which can then be used to produce methanol, if the syngas is produced from biomass (and waste) with CO^2 as a co-reactant. More than 75 percent of the methanol produced is generated from steam-reformed natural gas into syngas. Huixin *et al.,* [15] carried out research with kitchen waste conversion into syngas by a 1kW plasma gasification system. It was determined that steam injection enhances the production and efficiency of syngas, which is primarily the result of heterogeneous water gas shift reaction. The efficiency of the current system ranges from about 7% to 28.2%. Paulino *et al.,* [16] investigated the use of syngas from biomedical waste plasma gasification systems for electricity production. It was stated that the energy efficiency of the plasma gasifier is 78.58% and biomedical waste plasma gasification is capable of producing 31% of the required electricity. Through economic analysis, a payback period of 6 years was determined.

Previous study typically focused on the gasification of waste when using plasma gasification method. Hence, plasma gasification study using biomass feedstock seems to be scarce. The above findings driven this research, by carried out the conversion of energy from empty fruit bunches into high calorific value syngas using the plasma gasification method. The effect of equivalence ratio was investigated to identify the performance of plasma gasification in producing high-quality syngas.

2. Methodology
2.1 Feedstock Preparation

The present study was used pelleted empty fruits branch (EFB) of the palm oil as feedstock for the gasification process. Feedstock required some necessary step to prevent any disruption to the reactor and also to produce a high quality of gas product that imposed the raw sample in preparation for the pre-gasification process. EFB was collected from a palm oil mill industry (Heavy Oil Mill Sdn Bhd, Bahau – Keratong Highway, Mukim Bera, Pahang). The moisture content of the raw EFB was 74.9 wt%. The moisture content was then reduced from 74.9 to 7.4% via drying method using an oven at an operating temperature of 378 K for 24 hours. The dried sample was immediately placed in a sample bag to avoid its contamination. Figure 1 shows the empty fruit bunch pellet used for the entire process of gasification.

Fig. 1. Empty Fruit Bunch Pellet

2.2 Feedstock Characterization

The physiochemical properties of the oil palm EFBs, namely, moisture content (MC), volatile matter (VM), fixed carbon (FC), and ash content (AC) were measured via proximate analysis using a Thermogravimetric analysis (TGA) model LECO TGA-701. The weight of 9.804 mg of air-dried EFB powder was determined after it was placed in an alumina crucible and inserted into the TGA furnace. The proximate analysis was conducted with a rate of 20℃ min-1 from initial temperature 30℃ to 900℃). The EFB sample was continuously heated from initial temperature to a temperature of 110℃ at a rate of 20℃/min under nitrogen flow at the rate of 20 mL/min and hold for 10 minutes. Then, the temperature of the furnace was increased significantly to 900℃ at 20℃/min under 20 mL/min of nitrogen. The EFB sample heated at 900℃ for 20 minutes under 20℃/min oxygen to estimate the fixed carbon content. The residue was considered to represent the ash content.

Ultimate analysis was carried out to determine the elemental composition of the EFB. The analysis was performed using a CHNS/O Analyzer. The ultimate analysis provides information regarding the constituent elements of biomass, which include carbon (C), hydrogen (H), nitrogen (N), and sulphur (S). The percentage of oxygen (O) content found in the sample was acquired by subtracting one hundred percent from the total percentages of carbon (C), hydrogen (H), nitrogen (N), and sulphur (S). The results of the proximate and ultimate analysis are listed in Table 1.

Table 1
Proximate and Ultimate Analysis of Empty Fruit Bunch (EFB)

Proximate Analysis	Empty Fruit Bunch (wt%)
Moisture Content	8.683
Volatile Matter	70.663
Fixed Carbon	17.827
Ash Content	2.827
Ultimate Analysis	Empty Fruit Bunch (wt%)
Carbon	43.61
Hydrogen	9.88
Nitrogen	0.80
Sulphur	0.67

2.3 Experimental Design (Apparatus and Detail Procedure)

The experimental was conducted in a feed downdraft plasma gasifier using air as gasifying agent under various setup of flow rates as shown in Figure 2. The downdraft gasifier was heated using 9kW plasma arc which attached at the oxidation zone of the reactor. The gasifier temperature distribution was monitored using five thermocouples (denoted as T1 to T5) which was installed across the gasifier height. The gasifier was equipped with syngas conditioning process equipment including cyclone, cooling heat exchanger, oil filter, coal filter and gas sampling unit. All of the equipment was used for syngas cooling and cleaning purposed. The flare unit was installed to identify the presence of the combustible syngas. The air flow rate capacity was up to 60N/m^3 produced using 0.45kW suction blower and adjusted using a variable flow controller Series Dwyer rotameter. The particulate matter in the produced gas from the downdraft reactor was removed using cyclone separator. The steam of the produced gas was then condensed using cooling heat exchanger. The tar in the produced gas was then removed by oil and coal filter to avoid contamination and dirt before sampling. Perforated grate was installed at the bottom of the gasifier. The ash of the burned feedstock passed through the grate and settled in the ash pot at the bottom of the gasifier.

For the experimental procedure, 2kg EFB pellet was fed at the top of the reactor. The 9kW plasma generator was activated to produce plasma arc flame for gasification process. Air was supplied from surrounding via the suction blower. The air flowrate was adjusted using flow meter controller based on the estimated equivalent ratio ranged from 0.18 to 0.46. The gas outlet was then flared to assess the existence of combustible gas of syngas. The produced gas was then collected in the sampling bag through the sampling unit after being cleaned and cooled by cyclone, cooling heat exchanger, oil and coal filter. The collected gas was then analyzed using gas chromatography to evaluate the composition of syngas.

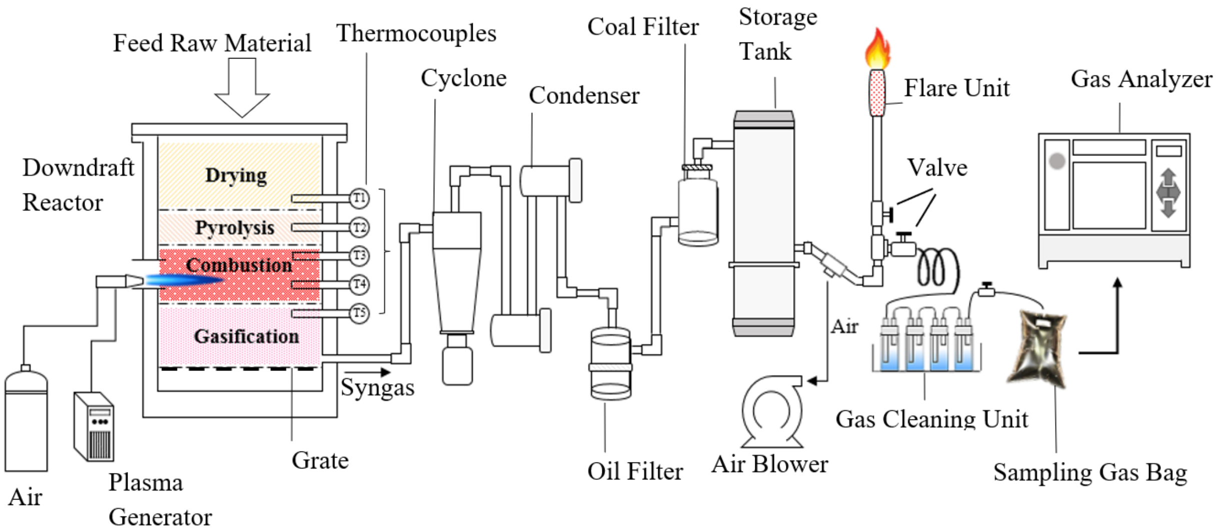

Fig. 2. Schematic diagram of thermal arc plasma suction downdraft gasification experimental setup

2.4 Measurement Method and Parametric Study

The chemical composition of syngas was analyzed using gas chromatography (GC) Agilent Technologies model 4890 which equipped with a thermal conductivity detector (TCD). Gas samples of syngas were taken out from a sampling bag by syringe and injected into the 15ft x 1/8 inches gas chromatography column containing 80/100 mesh Carboxen-1000 (Supelco, USA) with 2.1mm internal diameter was used to separates the permanent gasses. The oven temperature was set at 35°C and gradually increased to 210°C at a rate of 20°C/min. The injector and TCD detector were set at 150°C and 220°C with carrier gas flow rate (Helium) at 45mL/min.

The effect of equivalence ratio on the gasification performance including syngas composition, high heating value (HHV), cold gas efficiency (CGE), carbon conversion efficiency (CCE) and syngas yield was conducted by varying the inlet air flow rate from 100 to 250 LPM, which resulted in a range of equivalence ratio between 0.18 to 0.46. The set of operating parameters for the present study was summarized as in the Table 2.

Table 2
Operating Parameters for plasma gasification downdraft reactor

Parameter	Empty Fruit Bunch
Empty Fruit Bunch Pellet size (mm)	8
Mass per Batch (Kg)	2
Temperature (°C)	900
Equivalent ratio	0.18, 0.27, 0.36, 0.42, 0.46
Plasma current (Amp); Power (kW)	45; 9

The calculation of the LHV and HHV of EFB can be performed by using Eq. (1) [17] and Eq. (2) [17] respectively. LHV_{syngas} is the lower heating value of the syngas and HHV_{syngas} is the higher heating value. Both were used as a parameter to evaluate syngas quality.

$$LHV_{gas}(MJ/Nm_3) = (30\,x\,CO + 25.7\,x\,H_2 + 85.4\,x\,CH_4)\,x\,0.0042 \quad (1)$$

$$HHV_{gas}(MJ/Nm_3) = (H_2\,x\,30.52 + CO\,x\,30.18 + CH_4\,x\,85)\,x\,0.0041868 \quad (2)$$

The cold gas efficiency (CGE) is calculated as ratio of lower heating value of syngas to the lower heating value of solid/biomass as in Eq. (3) [18].

$$CGE = \left(\frac{Y_{gas} * HHV_{gas}}{HHV_{biomass}}\right)\% \tag{3}$$

The Carbon Conversion Efficiency (CCE) is the ratio of carbon in the syngas to the carbon in the biomass was determined according to Eq. (4) [17,18].

$$CCE = \left(\frac{12 * Y_{gas}(CO\% + CO_2\% + CH_4\%)}{22.4 * C\%}\right)\% \tag{4}$$

3. Results

The equivalence ratio of gasification is a measure that quantifies the amount of air/oxygen per unit mass of fuel relative to the amount of air/oxygen theoretically required for complete combustion. Therefore, the optimal equivalence ratio that promotes gasification (incomplete combustion) resulting in combustible gases such as CO over complete combustion with excess air supply that mostly produces CO_2 must be identified. The present study investigated the effect of various equivalent ratio including 0.18, 0.27, 0.36, 0.42 and 0.46 on the production of syngas via plasma downdraft gasification method. The biomass feed rate per batch was set constant at 4kg/hr.

Figure 3 showed the composition of CO, CO_2, H_2, and CH_4 with various equivalent ratio. The gas component of CO, H_2 and CH_4 were typically produced at the reduction zone. The concentration of CO in syngas was increased from 9.92 vol% to 13.08 vol% with the increased of equivalent ratio from 0.18 to 0.46. In general, it is known that higher temperatures favor reactants in exothermic processes and products in endothermic reactions [19]. Therefore, the significant increase in CO concentration at higher temperatures seems to be occurred due to the endothermic reduction reactions based on Eq. (5) and Eq. (6) [20].

$$Water - gas\ reaction: C + H_2O + Heat \leftrightarrow CO + H_2 \tag{5}$$

$$Boudourd\ reaction: C + CO_2 + Heat \leftrightarrow 2CO \tag{6}$$

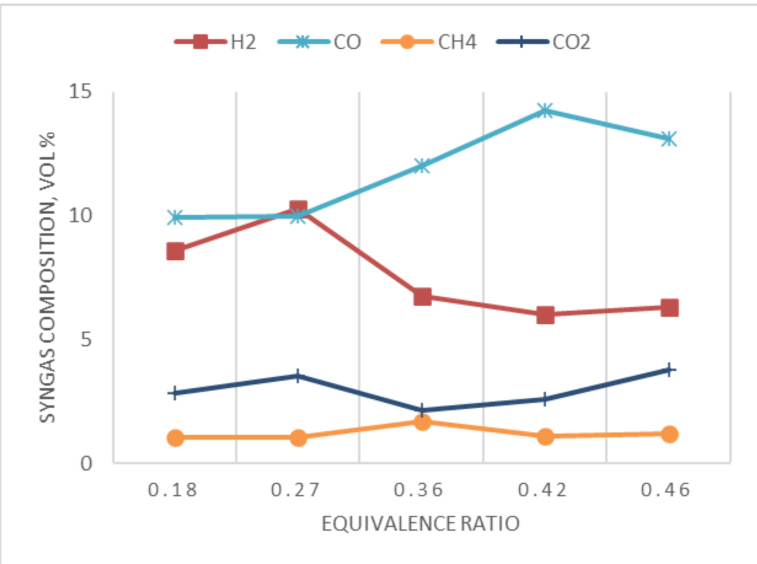

Fig. 3. Syngas composition (vol%) against Equivalence ratio

The composition of H_2 at equivalence ratio of 0.18 was 8.59 vol%. The composition of H_2 was maximum at 10.29 vol% at equivalence ratio of 0.27. The H_2 content was then decreased at 6.77 vol% and 6.012 vol% and slightly increase at 6.31 vol% at equivalence ratio of 0.36, 0.42 and 0.46 respectively. The composition of H_2 content was reduced as the presence of H_2O component from oxidation zone and moisture content of feedstock which then be used for water gas reaction (Eq. (4)) in reduction zone was reduced at higher equivalent ratio. Higher equivalent ratio as well as higher temperature accelerated the conversion H_2 to H_2O in oxidation zone hence reduced the number of available H radical. The reduced H radical hence reduced the formation of H_2O which require to produce H_2 via water gas reaction. The trend of produced H_2 composition in the present study was also reported by previous study which stated that the decrease in H_2 production was due to the increase of equivalence ratio that accelerated the oxidation and combustion reaction [21]. The gas composition of CH_4 was maximum at equivalence ratio of 0.36 with the value of 1.69 vol%.

Figure 4 illustrates the results of HHV against equivalence ratio. By applying Eq. (2), Figure 4 indicates how the equivalence ratio affects the HHV of an empty fruit bunch and this equation was applied to derive the HHV. The HHV increased with the increase in equivalence ratio up to a peak value of equivalence ratio at 0.36, which can be associated to the low CO_2, before it began to decline as the equivalence ratio increased [22]. Maximum HHV of 2.99 MJ/Nm^3 corresponds to the high concentration of combustible gases, particularly CH_4. Increasing the equivalence ratio to beyond 0.27 was disadvantageous for gas HHV due to the dilution of the producer gas by N_2 which in turn results in the gas low energy content.

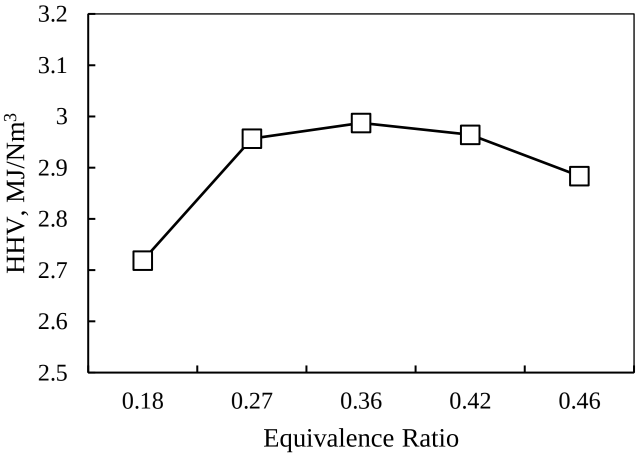

Fig. 4. Higher Heating Value (HHV) against Equivalence Ratio

Figure 5 showed the results of cold gas efficiency (CGE) against equivalence ratio. The value of CGE was calculated using Eq. (3). The CGE was 12.74 % at equivalence ratio of 0.18. The CGE was increase to 13.76% at equivalence ratio of 0.27. The value of CGE was maximum at equivalence ratio of 0.36 with efficiency of 14.27%. The CGE value was then decrease to 14.22% and 13.78% at equivalence ratio of 0.42% and 0.46% respectively. The value of CGE was correlated with the value of HHV and gas yield based on Eq. (3). Hence the maximum value of CGE was at equivalence ratio of 0.35 which was relatively at the same condition of the maximum value of HHV. The present CGE result was also in agreement with the previous study [23]. The reaction temperature, reaction time, feed concentration, and the usage of a catalyst are some of the other variables which could affect the CE/CGE value [24]. The CGE of the system could be increased by increasing the temperature, prolonging the reaction time, reducing feed concentration, and adding catalyst [24].

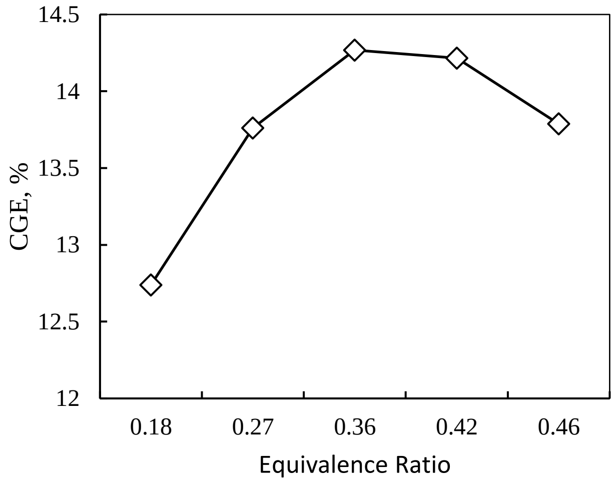

Fig. 5. Cold Gas Efficiency (CGE) against Equivalence Ratio

Figure 6 depicted the relation of the equivalence ratio with gas yield. The value of gas yield was 1.6 Nm^3/Kg at equivalence ratio of 0.18 and gradually increased to 4.10 Nm^3/Kg at equivalence ratio of 0.46. An increase in the air flow rate directly promotes the combustion reactions and thereby increases the combustion zone temperatures. This leads to an increase of temperature in the entire zones which then improving the feedstock conversion and produced higher quality of syngas. Gas yield improves with the increase in equivalence ratio due to the enhanced oxidation and char gasification reactions which indicated by the increase in production of CO from the conversion of carbon element in the feedstock.

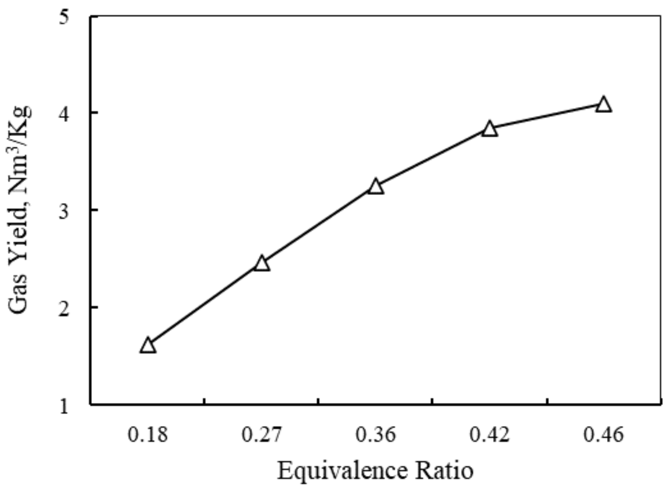

Fig. 6. Cold Gas Efficiency (CGE) against Equivalence Ratio

Figure 7 depicted the results of CCE against equivalent ratio. The value CCE was 27.48% at equivalence ratio of 0.18 and gradually increased to 91% at equivalence ratio of 0.46. The value CCE was correlated with the value of syngas yield. The CCE value was also increased with the increased of equivalence ratio which promoted the conversion process of carbon via oxidation process [20]. The combustion reactions in oxidation process are significantly augmented by an increase in air flow rate, which also enhances the temperatures in the combustion zone [25].

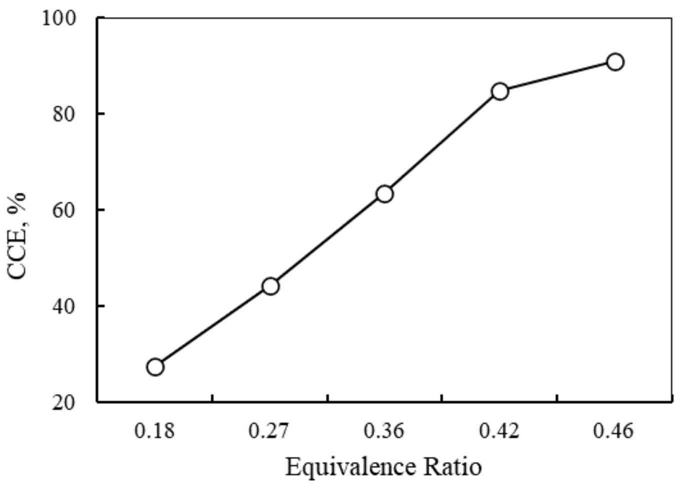

Fig. 7. Carbon Conversion Efficiency (CCE) against Equivalence Ratio

4. Conclusions

The present study investigated the gasification characteristic of EFB pellet using thermal arc plasma gasification method. The effect of different equivalent ratio on the produced syngas quality and the process performance including syngas composition, calorific value, cold gas efficiency, carbon conversion efficiency and syngas yield were evaluated. The results were reported as follow:

i. CO and H_2 content in produced syngas was increased and reduced respectively as the equivalence ratio increased. Production of CO increased as the temperature increase which promoted the water gas and Boudourd reaction. H_2 content was reduced as the presence of H_2O from oxidation zone and moisture content of feedstock for water gas reaction in reduction zone was reduced at higher equivalent ratio. Higher equivalent ratio as well as higher temperature accelerated the conversion H_2 to H_2O in oxidation zone hence reduced the number of available H radical.
ii. Higher heating value was observed at equivalent ratio of 0.36 where the amount of combustible gas of CH_4 was higher. Whereas the amount of CO and H_2 was balanced with H_2/CO ratio of 0.5. The CGE value was corresponded to the value of HHV where the maximum value was also at equivalent ratio of 0.36
iii. CCE and syngas yield was increased as the equivalent ratio increased which indicated the increase in production of CO from the conversion of carbon element in the feedstock.

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