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Effect of Feedstock Blends and Equivalence Ratio on the Thermal Arc Plasma Assisted Co-Gasification of Biomass and Plastic using Air-Blown Downdraft Reactor

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ABSTRACT

Plastic waste is known to cause an emerging environmental pollution, posing risks to both terrestrial and aquatic ecosystems. Co-gasification method is an alternative way to reduce municipal solid waste and plastic waste by converting it into useful gas fuel energy. The present study used empty fruit bunch biomass (EFB), plastic waste of low-density polyethylene (LDPE) and Polyethylene terephthalate (PET) as a feedstock for thermochemical conversion process into syngas fuel energy via plasma co-gasification method. The effect of multiple feedstocks mixture between biomass and plastic and equivalence ratio on the compositions of produced syngas, high heating value (HHV), lower heating value (LHV), cold gas efficiency (CGE) and carbon conversion efficiency (CCE) were critically investigated. A reactor of air-blown downdraft arrangement was used in these experiments. The gasifying agent flow rate of air was set at the frequency range of 10 to 22Hz to achieve equivalence ratio between 0.15 to 0.30. The blending ratio (BR) between biomass and plastic (EFB:Plastic) were set as E90:P10, E80:P20 and E70:P30. The results indicate that H_2 and CO composition is typically decrease as ER increase for the mixture of EFB and LDPE. In contrast, the composition of H_2 and CO is generally increase as ER increases. However, the maximum value of H_2 and CO is dominated by the mixture of EFB and LDPE at any blending ratio and lower ER condition. This is due to the higher element of H, C and O in the raw material of EFB and LDPE compared to PET. This study is crucial in understanding the synergistic effect of co-gasification assisted with plasma reaction between biomass and plastic waste.

1. Introduction

Urban communities are increasingly struggling with the significant challenge of Solid Waste Management (SWM) [1]. The present worldwide annual generation of municipal solid waste is

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estimated at approximately 2.01 billion tons, with projections indicating an anticipated increase to 3.4 billion tons by the year 2050 [2]. The current waste management system has been long introduced by government to reduce the solid waste generation problem including recycling, composting, incineration, and landfilling. However, those conventional method also caused environmental and health issues [3]. Incinerating waste typically emitted pollutants and toxic chemicals that caused a pollution to air. Whereas landfilled method carries the toxins from wastes into the soil and polluting the water that is supply to the residential community [4].

Recently, waste-to-energy technologies which also known as thermochemical conversion technologies such as thermal depolymerization, gasification and pyrolysis has been received much attention due to its benefits of reducing municipal waste from incineration and landfilling method [5,6]. There are recently more than 2500 waste-to-energy plants has been developed worldwide based on the previous research data [7]. One of the promising thermochemical conversion technologies that can potentially treat waste efficiently is Gasification. Gasification is a process that convert any carbon-based raw material into synthesis gas in a presence of gasifying agents [8]. Plasma gasification is a modified technique of conventional gasification method that utilizes a plasma torch or arch to generate gas. It is one of the conversion technologies with high energy efficiency and low hazardous emissions [9].

Plasma gasification method is beneficial in producing highly useful energy from hazardous waste and biomass [10]. However, plasma gasification operational process demonstrates a significant high expense compared to conventional method such as landfill and incineration. Hence, integration with other processes is critically required to reduce the plasma gasification operational costs. Co-gasification involves the simultaneous conversion of different feedstocks, such as biomass or waste materials, along with the primary material that involved in the gasification process. The combination of feedstocks can lead to synergies that may enhance the optimization of the overall process and costs reduction [11].

Oil palm which also known as Elaeis guineensis, is most widely grown and economically valuable oil crops in the world [12]. In year 2020, Malaysia had produced 19.4 million tonnes of palm oil [13]. During processing of palm oil, large amount of oil palm wastes (OPWs) such as Mesocarp Fibre (MF), Palm Kernel Shell (PKS), Palm Oil Mill Effluent (POME) and Empty Fruit Bunch (EFB) were generated [14]. In 2021, there is more than 124 million tons oil palm wastes produced from the palm oil mills [15]. In fact, oil palm wastes (OPWs) are harnessed for electricity generation, promoting a clean and sustainable energy source [16]. Hence, the abundance of generated oil palm waste or biomass is observed can potentially become a primary source of feedstock for co-gasification process [17].

Low Density Polyethylene (LDPE) is one type of plastic often used in restaurants, houses, and hotel, which accounting for 55% of the total plastic waste. It either ends up in irresponsibly discarded in natural environments or landfills [18]. Polyethylene terephthalate, commonly known as PET, is another type of plastic that contain a thermoplastic polymer. PET appear to be a highly abundance plastic material which globally demand for recycling purposes, since massive quantities of this waste can cause a serious environmental problem. However, there is only small fraction of PET is recovered and recycled [19]. Hence, plastics waste become an attractive source of material that can be used for thermochemical conversion of gasification process since plastic is derived from hydrocarbon compounds typically obtained from petroleum and it contain large amount of hydrogen in syngas. [20]. Thus, the present study intended to focus on evaluating the performance of thermal arc plasma co-gasification of a mixture comprised of plastic waste (LDPE/PET) and biomass (EFB).

Numerous co-gasification experiments involving various biomass sources have been extensively studied in Malaysia [21]. Inayat *et al.,* [22] investigate the syngas quality from gasification and co-gasification of oil palm fronds (OPF) and coconut shells (CS). The results indicate that there was an increase of up to 18% in CO, 16% in H_2 and 14% in syngas higher heating value when compared to the gasification of individual biomass [22]. However, co-gasification of different types of biomasses presents a challenge. This is because the resulting syngas contains a significant amount of carbon dioxide (CO_2), which diminishes both its syngas quality and calorific value [23]. One viable solution involves substituting one of the biomass feedstocks with plastic waste [24]. Moghadam *et al.,* [25] investigated the co-gasification of palm kernel shell and polyethylene waste blend with steam as gasifying agent. The study claimed to have achieved production of an enriched syngas with a gas yield of maximum value 87.73 vol% [25]. Basha *et al.,* [26] conducted a study of air co-gasification performance between palm kernel shell and PS in different operating conditions. The study found that the increases in temperature and equivalent ratio increased the amount of produced syngas [26].

While there have been numerous co-gasification experiments conducted in Malaysia, the combination of biomass and plastics in co-gasification processes has received relatively limited attention in research. In addition, a correlation of reaction between biomass-plastic co-gasification assisted with plasma reaction is yet not fundamentally understood. Hence, the present study aims to investigates the effect of varying the ratio of the multiple feedstock mixtures on the composition of produced syngas specifically using the combinations of LDPE with EFB and PET with EFB in the plasma air co-gasification reactor. This research is essential for gaining an insight of the effect of different equivalence ratio and feedstocks blending ratio on the syngas composition (H_2, CO, CO_2 and CH_4), Higher Heating Value (HHV), Lower Heating Value (LHV), Cold Gas Efficiency (CGE) and Carbon Conversion Efficiency (CCE).

2. Methodology

2.1 Material Preparation

Feedstocks used in this co-gasification process consisted of empty fruit bunch (EFB) pellet, Low-density polyethylene (LDPE) and Polyethylene terephthalate (PET) plastic waste, which are shown as Figure 1. The biomass pellets were cylindrical, with a diameter of about 1 cm and a length of 2.5 cm ± 0.5 cm. They were obtained from Havys Oil Mill Sdn Bhd, a palm oil mill industry located at Bahau – Keratong Highway, Mukim Bera, Pahang. The biomass pellets were made from palm oil trees. The LDPE plastic was food plastic waste, and the PET plastic was plastic bottles waste. They were collected from landfill - Tapak Pelupusan Sisa Pepejal Majlis Perbandaran Teluk Intan, located at Perak. Both types of plastic waste were cut into small pieces of about 1.0 cm ± 0.5cm.

(a) (b) (c)

Fig. 1. Feedstock used for air-blown plasma assisted gasification (a) EFB pellets biomass, (b) PET plastic waste and (c) LDPE plastics waste

Table 1 summarized the properties of all the feedstock used in this study. The properties of moisture content, volatile matter content, fixed carbon, and ash content were characterised using the proximate analysis via the thermogravimetric analysis (TGA) measurement. Whereas the properties of the elemental composition including carbon, C, Hydrogen, H, Nitrogen, N, Sulfur, S and others for all the feedstock was characterised using ultimate analysis via the measurement of CHNS/O Analyzer.

Table 1
Feedstock properties of proximate and ultimate analysis

	Type of feedstock		
	EFB	PET	LDPE
Sample weight (mg)	1.645	1.949	1.782
Proximate analysis (wt%)			
Moisture Content, MC	8.683	0.731	0.229
Volatile Matter, VM	70.663	98.726	98.553
Fixed Carbon, FC	17.827	-	-
Ash Content, AC	2.827	0.543	1.218
Ultimate analysis (wt%)			
Carbon, C	43.61	62.21	73.07
Hydrogen, H	9.88	3.71	17.26
Nitrogen, N	0.8	0.06	0.51
Sulphur, S	0.67	0.16	0.89
Others	45.04	33.86	8.27
HHV (J/g)	17219	22378	36259

2.2 Experimental Instruments and Procedures

Figure 2 shows the schematic diagram of thermal arc plasma downdraft gasification experimental setup. There are various type of instruments, tools and equipment used in this experiment to achieve its objectives, which including weight scale, downdraft gasifier, air blower, gas barrel, plasma generator, cyclone, condensers, oil filter, coal filter, valves, flare unit, gas lighter gun, gas cleaning unit, sampling gas bag and gas analyser.

A mixture of 1kg of EFB pellets and 100g of LDPE waste was prepared for the blending ratio of E90:P10. This mixture was loaded into the downdraft gasifier from the top and sealed with a lid. The plasma generator was switched on to produce a 9kW plasma arc flame. A pipe connected the gasifier body to a suction blower that drew in air from the environment. The air flowrate was set using a frequency controller with a range of 10Hz to 22 Hz which is equivalent to ER of 0.15 to 0.21.

The producer gas was first cleaned by a cyclone filter that separated solid particles from the syngas. Then a condenser to cool it down and finally an oil and coal filter for further cleaning. The syngas was split into two streams: one to the flare unit and the other to the gas cleaning unit with a peristaltic pump. The syngas in the flare unit was ignited with a gas lighter gun to check if it was combustible. A peristaltic pump in the gas cleaning unit ensured a consistent and controlled flow of syngas and reduced the risk of contamination. The syngas was then stored in a sample bag and sent for analysis using a Gas Chromatograph to determine its composition. Each experiment lasted for 13-16 minutes and collected 5 sample bags. The experiment was repeated for different blending ratios and feedstocks according to Table 2.

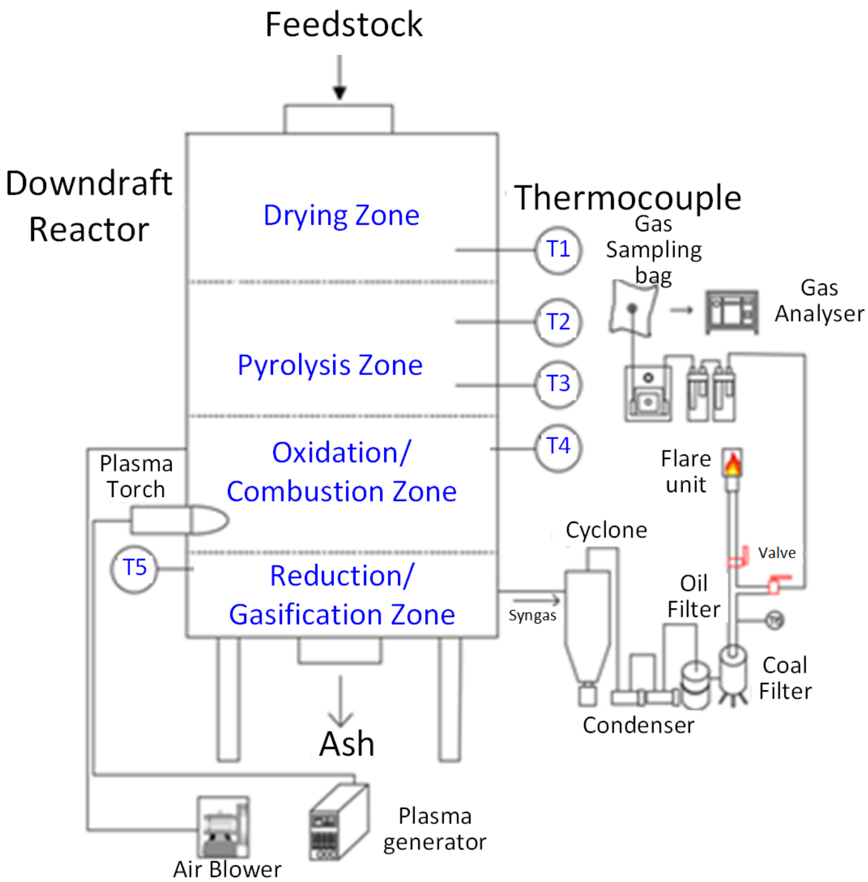

Fig. 2. In this case simply justify the caption so that it is as the same width as the graphic

Table 2
Operational setup for plasma assisted co-gasification of EFB biomass and plastic

Frequency (Hz)	Equivalence ratio	Blending ratio		
EFB-LDPE				
10	0.15	90:10	80:20	70:30
12	0.17	90:10	80:20	70:30
14	0.19	90:10	80:20	70:30
16	0.21	90:10	80:20	70:30
EFB-PET				
13	0.18	90:10	80:20	70:30
16	0.21	90:10	80:20	70:30
19	0.24	90:10	80:20	70:30
22	0.27	90:10	80:20	70:30

2.3 Quantitative Analysis

The experimental data was analysed using a quantitative method. The equations for Equivalence Ratio (ER), Carbon Conversion Efficiency (CCE), Cold Gas Efficiency (CGE), Higher Heating Value (HHV) and Lower Heating Value (LHV) were taken from the previous research. ER is calculated by the ratio of the actual air to feedstock ratio on mass basis to the stoichiometric amount of air to feedstock ratio which present in Eq. (1)

$$\mathrm{ER} = \frac{(\frac{\mathrm{Fuel}}{\mathrm{Air}})\mathrm{Stoichiometric}}{(\frac{\mathrm{Fuel}}{\mathrm{Air}})\mathrm{Actual}} \quad (1)$$

where AF_{actual} is an actual air-fuel ratio, which defined as a flowrate of oxidiser divided with the amount of feedstock. $AF_{stoichiometric}$ is the quantity of air needed for complete combustion of the feedstock to occur divided with the quantity of feedstock. Yield gas, γ_{gas} is critical parameter in evaluating the efficiency and performance of the gasification process, which express in terms of volumetric flowrate of syngas to the flowrate of feedstock as shown in Eq. (2).

$$\gamma_{\mathrm{gas}}\ (\mathrm{m^3/kg}) = \left(\frac{\mathrm{V_{syngas}}}{\mathrm{m_{feedstock}}}\right) \quad (2)$$

where V_{gas} is the flow rate of the syngas which specified as the flow rate of dry gas in volumetric base of m^3/h. Whereas $Mass_{Feedstock}$ is the feeding rate of feedstock in kg/h. CCE is the ratio of number of moles of carbon in the syngas to the total carbon in the feedstock which present in Eq. (3) [27].

$$\mathrm{CCE}\ (\%) = \left(\frac{12\times\gamma_{\mathrm{gas}}(\mathrm{CO\%}+\mathrm{CO_2\%}+\mathrm{CH_4\%})}{22.4(\mathrm{C\%})}\right) \quad (3)$$

where CO, CO_2 and CH_4 are the concentration of carbon-constituent gases in syngas in volumetric percentage and C is the carbon material in feedstock. CGE is the ratio of Higher Heating Value (HHV) of syngas with yield gas to the HHV of feedstock which present in Eq. (4).

$$\mathrm{CGE}\ (\%) = \left(\frac{\gamma_{\mathrm{gas}}(\mathrm{HHV})_{\mathrm{gas}}}{\mathrm{HHV_{feedstock}}}\right) \quad (4)$$

where HHV is defined as the higher heating value of the produced syngas, γ_{gas} is the gas yield in m^3/kg. and $HHV_{feedstock}$ is the higher heating value of the feedstock. LHV and HHV are important metrics used to characterize the energy content of a fuel, including syngas produced through gasification. These values represent the amount of heat released when a given quantity of fuel undergoes complete combustion under specific conditions which calculated by using Eq. (5) and Eq. (6).

$$\mathrm{LHV}\ (\mathrm{MJ/Nm^3}) = \frac{12.63(\mathrm{CO})+10.8(\mathrm{H_2})+35.82(\mathrm{CH_4})}{100} \quad (5)$$

$$\mathrm{HHV}\ (\mathrm{MJ/Nm^3}) = \frac{12.63(\mathrm{CO})+12.75(\mathrm{H_2})+39.82(\mathrm{CH_4})}{100} \quad (6)$$

where $H_2/100$, $CO/100$ and $CH_4/100$ were the constituent of gaseous component in produced syngas.

3. Results

3.1 Effect of Feedstock Blending and Equivalence Ratio on the H_2 and CO Composition

This section explains the effect of different equivalence ratio (ER) on the syngas composition of H_2, CO, CO_2 and CH_4 using EFB and plastic (LDPE or PET) blending ratio (BR) of 90% EFB and 10% plastic (E90:P10), 80% EFB and 20% plastic (E80:P20) and 70% EFB and 30% plastic (E70:P30). Figure 3 showed the effect of ER on the syngas composition using BR of 90% EFB and 10% plastic. Figure

3(a) showed the production of H_2 in syngas was decreased from 5.87 vol% to 3.36 vol% with the increased of equivalence ratio for the mixture of EFB and LDPE at E90:P10. However, H_2 composition was increased from 0.63 vol% to 6.52 vol% as ER increase for the mixture of EFB and PET. The minimum concentration of H_2 was produced using the mixture of EFB and PET with ER of 0.18 and BR of E90:P10 which is 0.63 vol%. The increased concentration of H_2 in the mixture of EFB and PET can be explained by the amount of oxygen supplied to the plasma gasifier. An increase in ER results in an increase in oxygen supply, leading to a high degree of combustion reaction based on the Eq. (7) and Eq. (8) [28]. The heat from combustion zone increased as ER increased which caused the endothermic reaction to occur in gasification zone, thus promoting the water-gas shift reaction and hence produced higher H_2 and CO based on Eq. (9). In contrast, the composition of H_2 was decrease with ER for the mixture of EFB and LDPE. The lower amount of LDPE in the blending mixture seems to promote higher rate of complete combustion. The extended reaction of combustion at higher ER will produce H_2O based on the Eq. (7) which caused the amount of H_2 composition to decrease. The result agrees with Guo *et al.,* [29] which also reported that H_2 concentration decreased as ER increased.

Combustion reactions

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \text{ (}H_2\text{ oxidation)} \tag{7}$$

$$CO + \frac{1}{2} O_2 \rightarrow CO_2 \text{ (CO oxidation)} \tag{8}$$

Water-gas shift reaction

$$C + H_2O + Heat \leftrightarrow CO + H_2 \tag{9}$$

Boudouard reaction

$$C + CO_2 + Heat \leftrightarrow 2CO \tag{10}$$

Figure 3(b) illustrate the composition of CO in syngas was increased as ER increased for both mixture of EFB and LDPE, and EFB and PET. The increase in ER causing the increase in water-gas shift reaction temperature which then promote the endothermic reaction [30]. Hence, the production of CO increase as ER increase. However, syngas composition was minimum at ER 0.19 and 0.24 for the mixture of EFB and LDPE, and EFB and PET respectively. The slightly decreased composition of CO in ER 0.19 for the mixture of EFB and LDPE was seemed to cause by the oxidation of CO to CO_2 which is due to the increase amount of air supplied. However, although the amount of air supply increased for complete reaction of CO into CO_2 through oxidation at higher ER of 0.22, the composition of CO was somewhat increase which indicate the gasification process favours the water gas shift reaction rather than oxidation reaction. The extreme high temperature of plasma appeared to enhance the cracking component H_2O to produce CO and H_2 through water-gas shift reaction. The decrease composition of CO for the mixture of EFB and PET at ER of 0.24 was also due to the equilibrium condition of water-gas shift reaction, where the increase amount of produced H_2 hindered the production of CO gas component. A minimum value of CO, which is 4.1 vol% produced at the mixture of EFB and PET with ER 0.18.

Figure 3(c) and Figure 3(d) showed the effect of ER on syngas composition for BR of 80% EFB and 20% plastic. Figure 3(c) showed the production of H_2 in syngas for the mixture of EFB and LDPE was slightly increased from 9.8 vol% to 9.93 vol% but then decreased to 3.86 vol% as ER increased. The composition of H_2 was slightly decreased from 3.49 vol% to 2.09 vol% then increased to 5.59 vol% and decreased to 4.40 vol% as ER increased for the mixture of EFB and PET. The produced composition of H_2 and CO seems identical for the mixture EFB and LDPE for BR of 80% EFB and 20% plastic with the previous BR of 90% EFB and 10% plastic where the composition was typically decrease as ER increase. The increased in ER was generally caused by the increased in oxygen supplied leading to a high temperature of gasification reaction which enhance the production of syngas. However, extended supplied of O_2 caused an oxidation reaction to occur which convert the component of H_2 and CO into inert component of H_2O and CO_2. Thus, the component of H_2 and CO were decrease as ER increased. The result agrees with the previous study which also indicates that the increased in ER showed adverse effects for H_2 and CO formation [27]. The mixture of EFB and PET exhibited an increase profile as ER increase. However, the increase profile of produced CO and H_2 for the BR of 80% EFB and 20% plastic were not significant compared to BR of 90% and 20%. The increase in plastic composition somewhat hindered the production of syngas at higher ER. This can be explained by the element of O in EFB which can enhance the oxidation reaction. The element of O in EFB is higher compared to PET based on Table 1.

The higher content of PET which attribute lower element of O reduce the available element of O in the EFB which resulted to a lower oxidation reaction as well as temperature. The lower temperature hence reduces the tendency of endothermic reaction to produce syngas. Figure 3(e) and (f) illustrates the effect of ER on the syngas production using BR of 70% EFB and 30% plastic. The profile of produced CO and H_2 seem identical with the BR of 80% EFB and 20% plastic. The result showed that the composition of H_2 and CO were decreased for the mixture of EFB and LDPE as ER increased. The decreased of H_2 and CO was resulted from the complete reaction into CO_2 and H_2O by the oxidation reactions which is due to the excessive supply of oxygen and higher content of O element for both EFB and LDPE which also assist the combustion and temperature based on the Table 1. Whereas for the mixture of EFB and PET, the composition of H_2 and CO was only decreased at ER 0.18, then increased as ER increased as shown in Figure 3(e) and Figure 3(f).

The increased of H_2 and CO composition was due to the high temperature reaction which favours to produce the high amount of H_2 and CO [31]. The increase in plastic content from 20% to 30% for the mixture of EFB and PET increase the element of O in the feedstock mixture. This increases the temperature of reaction for 30% PET compared to 20% PET hence increase the tendency of endothermic reaction to produce syngas. The maximum value of H_2 composition was 12.87 vol% at the ER of 0.17 for the mixture of EFB and LDPE with BR of E70:P30.

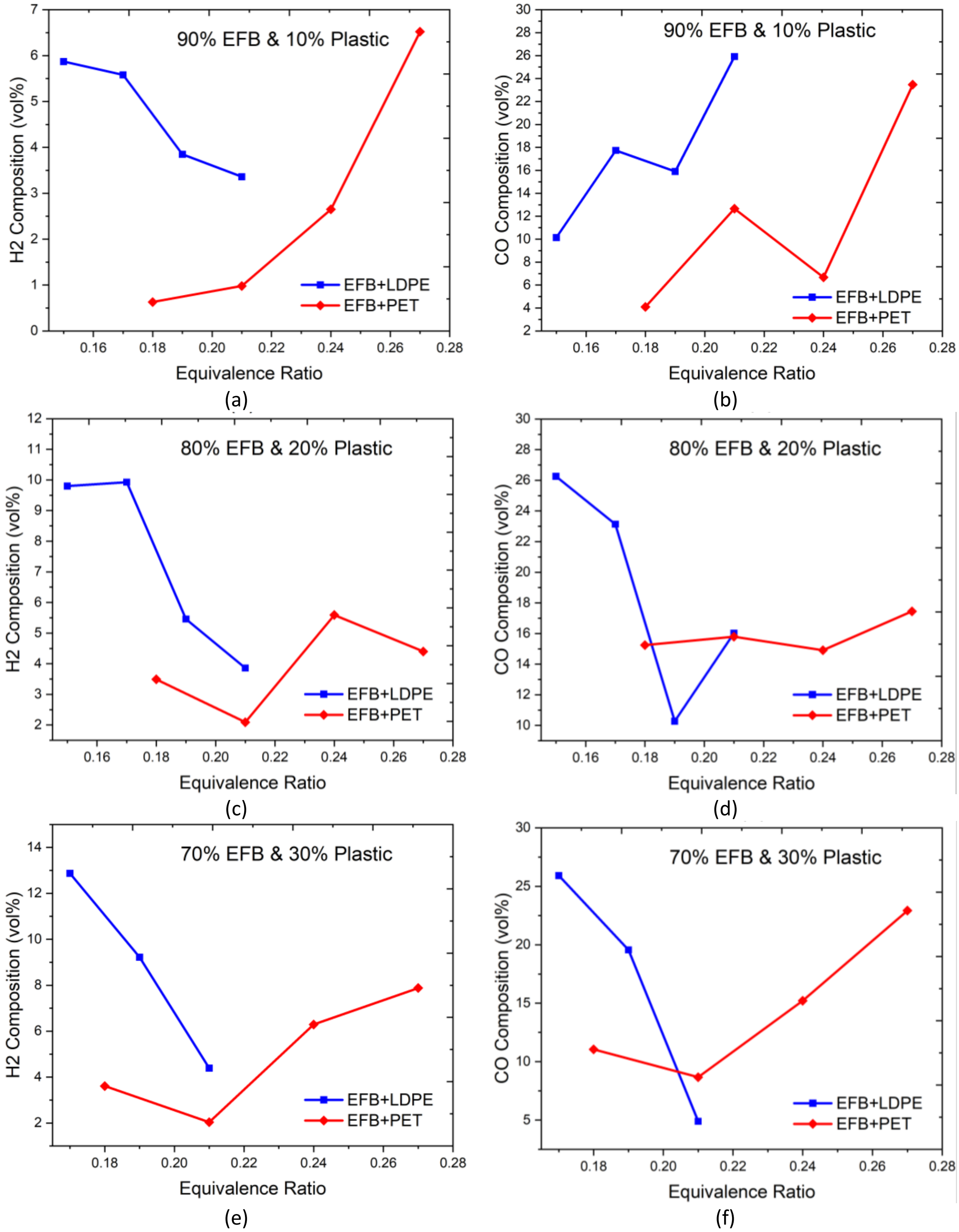

Fig. 3. The compositions of H_2 and CO against ER for EFB-LDPE and EFB-PET at different blending ratio of (a) E90:P10 for H_2 (b) E90:P10 for CO (c) E80:P20 for H_2 (d) E80:P20 for CO (e) E70:P30 for H_2 (f) E70:P30 for CO

3.2 Effect of Feedstock Blending and Equivalence Ratio on the Value of LHV, HHV, CGE, CCE and Gas Yield

This Figure 4(a) and Figure 4(b) showed the effect of ER on HHV and LHV of syngas for BR of 90% EFB and 10% plastic. HHV and LHV is determined by the concentration of combustible components in syngas including H_2, CO and CH_4 as shown in Eq. (5) and Eq. (6). The result showed that HHV and LHV was increased as ER increased. This is due to the high temperature resulted from the increased of air supplied which then promote the water-gas shift and Boudouard reaction (Eq. (9) and Eq. (10)) and hence improve the concentration of produced combustible components in syngas. There was a decreased trend occurred at ER 0.17 and 0.21 for the mixture of EFB and LDPE and EFB and PET respectively which resulted from the decreased amount of produced CO as depicted from the previous section of Figure 3.

Figure 4(c) and Figure 4(d) depicted the effect of ER on the HHV and LHV value for the BR of 80% EFB and 20% plastic. The result showed that HHV and LHV value was generally decreased as ER increased for the mixture of EFB and LDPE. Whereas HHV and LHV value was increased for the mixture of EFB and PET as ER increase. The HHV and LHV value were directly correlated with the concentration of CO and H_2. Hence, HHV and LHV were either increase or decrease with the increase or decrease of CO and H_2.

Figure 4(e) and Figure 4(f) illustrated the effect of ER on the HHV and LHV value using BR of 70% EFB and 30% plastic. HHV and LHV value exhibited identical trend with the composition of H_2 and CO for both mixtures since HHV and LHV value was directly proportional with the composition of H_2 and CO base on the Eq. (5) and Eq. (6). The maximum HHV and LHV value were 5.62 MJ/Nm^3 and 5.3 MJ/Nm^3 respectively at ER 0.17 for the mixture of EFB and LDPE. Whereas the minimum amount of HHV and LHV were produced at ER 0.18 for the mixture of EFB and PET with BR of 90% EFB and 10% PET, which were 0.86 MJ/Nm^3 and 0.83 MJ/Nm^3 respectively. This indicates that the syngas produced using the mixture of EFB and LDPE exhibited higher maximum calorific value compared to the mixture of EFB and PET. This is not surprising as LDPE generally contain higher component of ‘C’ and ‘O’ that can assist the production of CO and H_2 than PET in its raw material.

Figure 5(a) and Figure 5(b) illustrates the effect of ER on the CGE and CCE value for the BR of 90% EFB and 10% plastic. CGE is the ratio of energy content with the yield of syngas to the energy content of solid fuel which shown as in Eq. (4). The value of CGE is hence typically exhibited an identical profile with HHV value [32]. Figure 5(b) showed that the CCE was linearly increased as ER increased. The increase of ER indicated the increase of O_2 which resulted on the enhancement of the gasification reaction to produce CO, CH_4 and CO_2. The increased of CCE also can be explained through the Eq. (3) where it is directly proportional with the amount of produced CO, CH_4 and CO_2. Since the CCE value is the ratio of the carbon content in the produced gases with yield gas to the carbon content in the original feedstock, it is thus straightforward that CCE value increased as the yield gas as well as the composition of CO, CH_4 and CO_2 increased with ER as shown in Figure 5(b), Figure 5(d) and Figure 5(f).

Figure 5(c) shows the effect of ER on the CGE value for the BR of 80% EFB and 20% plastic. The distribution of CGE value demonstrated a slightly identical profile with HHV value. The presence of yield gas value in the CGE equation also attributed a significant effect on the CGE value. Hence, CGE value for the mixture of EFB and LDPE was lower compared to EFB and PET because of lower distribution of yield gas (Figure 6) despite having higher distribution of HHV. Figure 5(d) showed that CCE value for both mixtures attributed an identical profile with the yield gas value based on formulation by the Eq. (3).

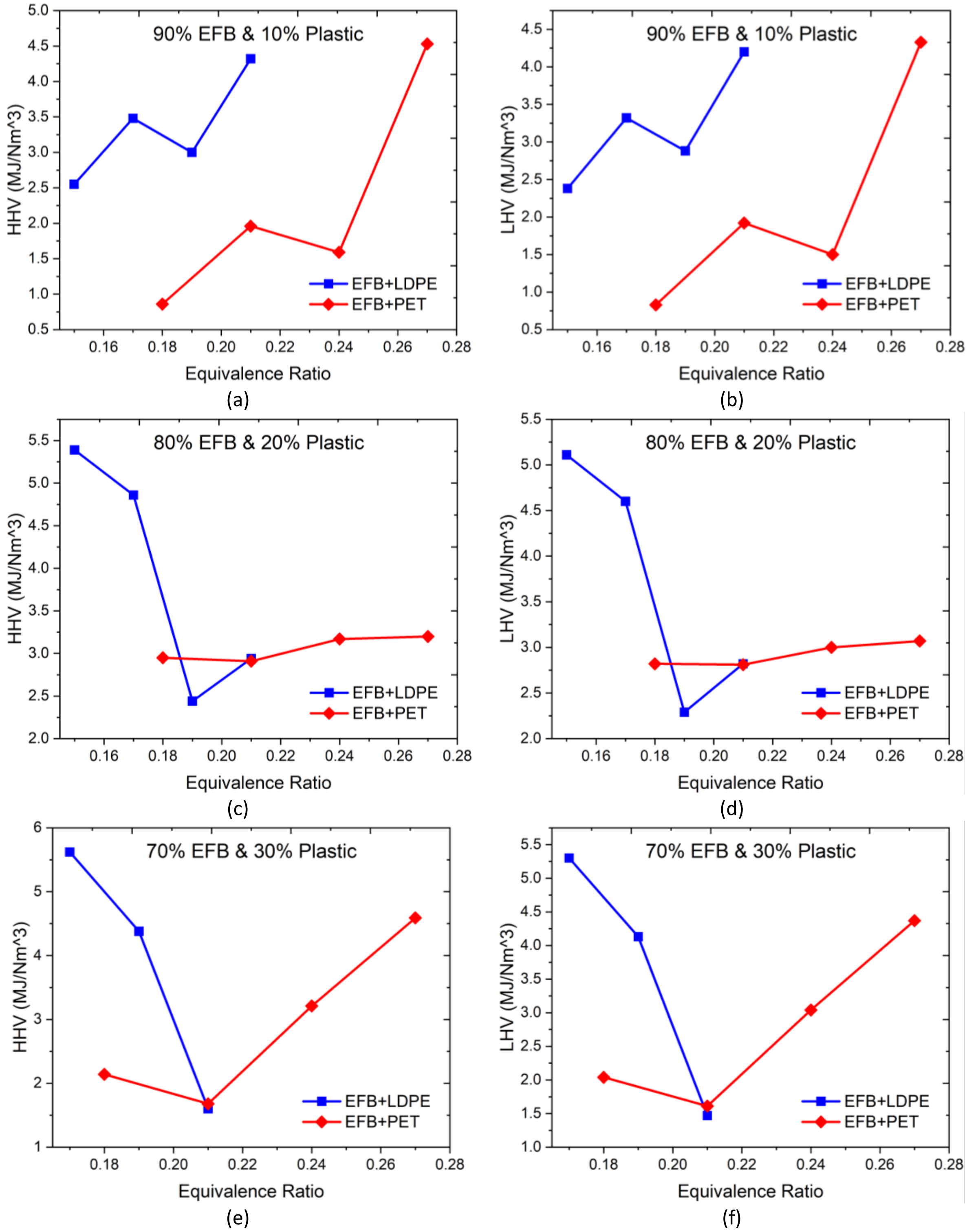

Fig. 4. The HHV and LHV value against ER for EFB-LDPE and EFB-PET at different blending ratio of (a) E90:P10 for HHV (b) E90:P10 for LHV (c) E80:P20 for HHV (d) E80:P20 for LHV (e) E70:P30 for HHV (f) E70:P30 for LHV

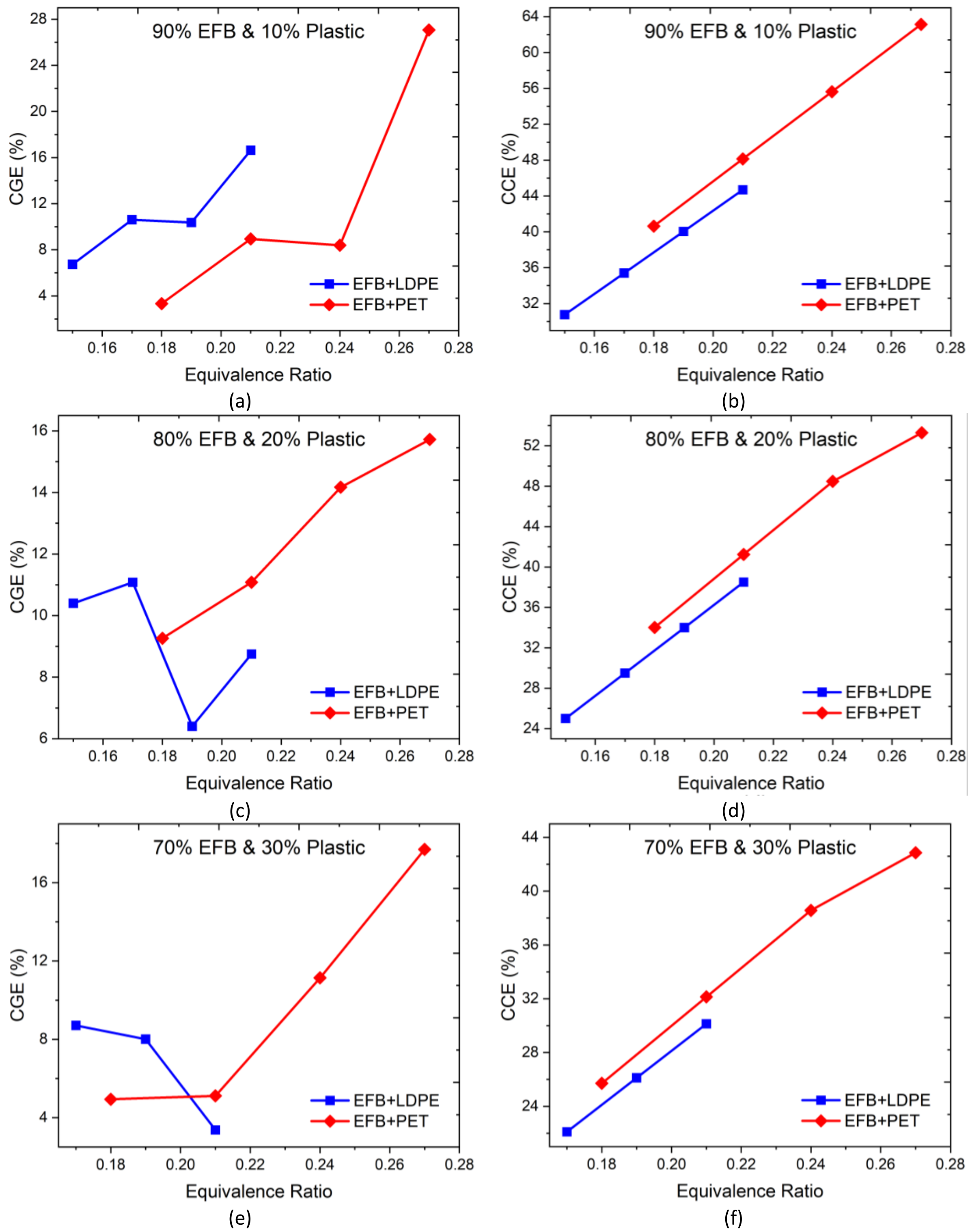

Fig. 5. The CGE and CCE value against ER for EFB-LDPE and EFB-PET at different blending ratio of (a) E90:P10 for CGE (b) E90:P10 for CCE (c) E80:P20 for CGE (d) E80:P20 for CCE (e) E70:P30 for CGE (f) E70:P30 for CCE

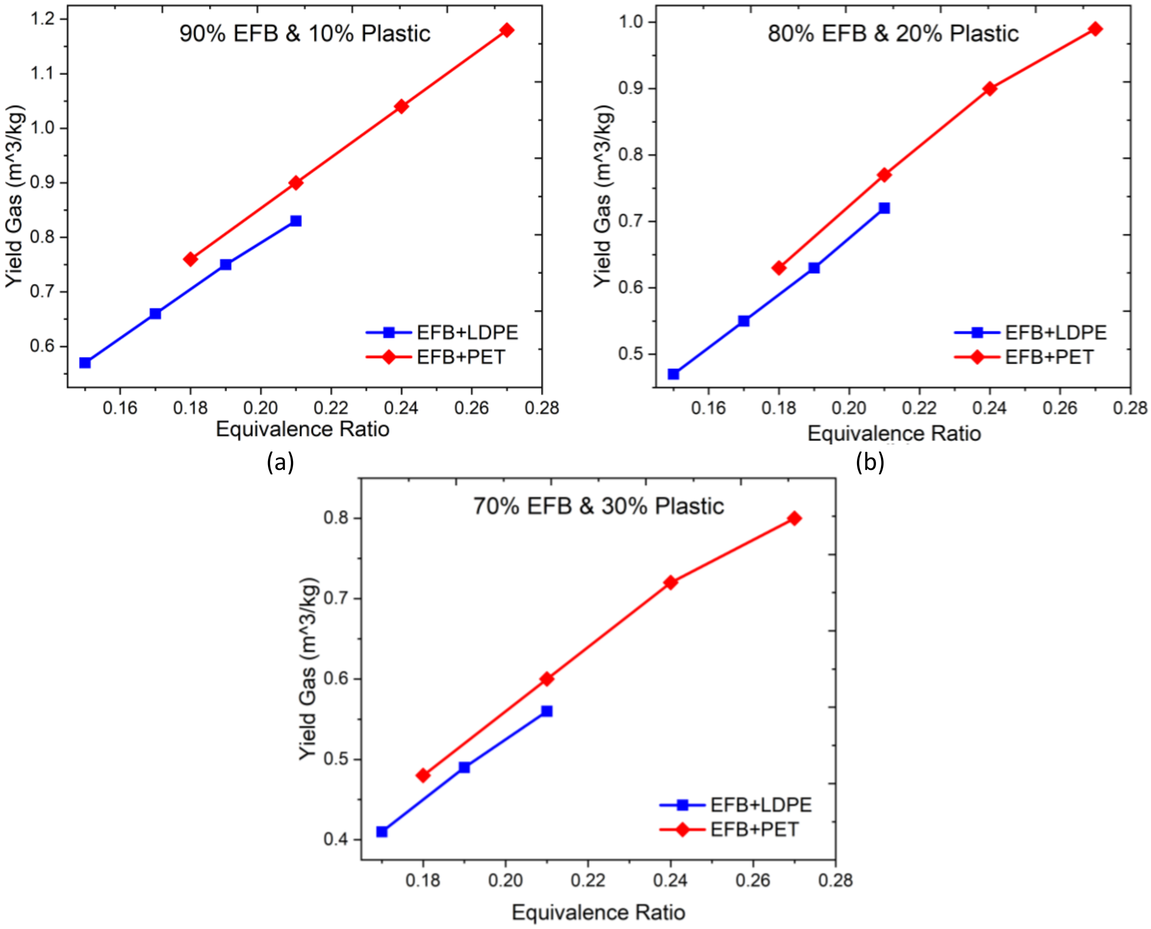

Fig. 6. The gas yield against ER for EFB-LDPE and EFB-PET at different blending ratio of (a) E90:P10 (b)D E80:P20 (c) E70:P30 for CGE

The distribution of CCE value was again higher for the mixture of EFB and PET compared to EFB and LDPE which indicate the total produced gas was higher using the mixture of EFB and PET. However, this does not mean the mixture of EFB and PET produce higher combustible gas since it is including inert gas element in the total produced gas. Figure 5(e) showed the result of CGE value against ER for BR of 70% EFB and 30% plastic. The value of CGE for each mixture was correlated with the values of HHV and yield gas based on the Eq. (4). Hence, CGE was decreased as ER increased for the mixture of EFB and LDPE but increased for mixture of EFB and PET. Figure 5(f) shows that the CCE is increased as yield gas increased as shown in Figure 6(c) which based on the Eq. (3).

The minimum amount of CGE was produced at ER 0.18 for the mixture of EFB and PET with BR of 90% EFB and 10% PET, which was 3.33%. Whereas the maximum amount of CGE was 27.02% also produced by the mixture of EFB and PET. This indicate that the higher amount of EFB increase the CGE value. In contrast, the presence of plastic in the feedstock mixture typically reduced the CGE value since the presence of PET in the mixture attribute the minimum value of CGE at lower ER. In addition, the increase of plastic content from 10% to 30% also reduce the range of CGE value for both type of mixtures. The minimum CCE and yield gas value were 22.1% and 0.41 m^3/kg respectively which produced at ER 0.17 using the mixture of EFB and LDPE with the BR of 70% EFB and 30% plastic. Whereas the maximum amount of CCE and yield gas were 63.13% and 27.02% respectively. This indicates that the mixture of EFB and PET typically produce higher total produced syngas, but it does not mean higher combustible gas as it is also included other non-combustible gas such as CO_2 and N_2.

4. Conclusions

The current study establishes the performance of air-blown plasma assisted co-gasification of EFB-LDPE and EFB-PET mixture in a downdraft gasifier. The present study aims to investigate the effect of equivalence ratio on the composition of H_2 and CO production at different blending ratio (BR) of EFB-LDPE and EFB-PET mixture. It is principally reported that the gasification reactions temperature of all zones increased as the equivalence ratio increased, resulting in a better quality of produced syngas. However, high amount of air supply tends to cause the complete combustion to occur which decreased the quality of syngas. The result shows that the composition of H_2 concentration is typically decrease as equivalence ratio increase from 0.15 to 0.21 for the blend mixture of EFB-LDPE using all type of BR (E90:P30, E80:P20 and E70:P30). The composition of CO for EFB-LDPE mixture also decreased for BR of E80:20 and E70:P30. The exceptional was only for BR of E90:P10 where the composition of CO was increased with the increase of ER. The composition of H_2 and CO was generally exhibited an increase profile with the increase of ER for the blend mixture of EFB-PET at any BR. However, a slightly decrease trend also occur at some value of ER. The maximum value of H_2 and CO composition, HHV and LHV were frequently produced at ER 0.17 with BR of E70:P30 for the EFB-LDPE mixture, with the values of 38.78 vol%, 5.62 MJ/Nm^3 and 5.3 MJ/Nm^3 respectively. This indicates that the gasification of higher content of LDPE in the feedstock mixture at lower ER demonstrated a better composition characteristic of produced syngas. However, the gasification of EFB-PET mixture with BR of E90:P10 at ER of 0.27 was produced the maximum value of gas yield, CGE and CCE, with the values of 1.18 m^3/kg, 27.07% and 63.13% respectively. Higher carbon contained gas produced by EFB-PET become a primary factor that contribute to the higher CGE, CCE and yield gas value. However, this is not always an indicator to the characteristic of good quality of syngas as it is also considered the composition of non-combustible gas like CO_2 and N_2.

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