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# Empty fruit bunch (EFB) gasification in an entrained flow gasification system

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**Abstract:** Biomass has become one of the most commonly used renewable sources of energy in the last two decades. Empty fruit bunch (EFB) is one of the examples for the biomass that is used as a renewable energy source. From the palm oil processing industry, only 10% are the final products such as palm oil and palm kernel oil, while the remaining 90% are harvestable biomass waste in the form of EFB, palm kernel shell (PKS) and oil palm frond (OPF). This overload amount of biomass waste will cause an abundance of waste which will also affect the environment. To convert EFB into usable energy in ways that are more efficient, less polluting, and economical, gasification has merge as one of the most favorable technological innovations in synthesis gas (syngas) production. The main aim of this work is to study the EFB gasification in an entrained flow gasification process based on the different operating temperature (700°C to 900°C) and equivalence ratio, ER (0.2 – 0.4), evaluated based on the production of gases such as hydrogen ($H_2$), carbon monoxide (CO), carbon dioxide ($CO_2$) and methane ($CH_4$). It was found that as the temperature was increased from 700°C to 900°C, the production of $H_2$ and $CO_2$ increased while CO was decreased. The optimum ER value of 0.30 was found to attain the highest Cold Gas Efficiency (CGE) value of 74.03% at 900°C.

***Keywords:*** *Renewable energy; Empty fruit bunch; Gasification; Entrained flow gasifier; Equivalence ratio.*

## Introduction

Biomass is a source of abundant, environmentally friendly, and renewable energy, and it may be an ideal alternative to fossil fuels for syngas production.[1] At the moment, biomass is catering for 14% of the world's total energy consumption it is ranked fourth among the primary energy sources in the world such as coal, oil and natural gas.[2] Having the general chemical formula of CxHyOz[3], it is an important source of energy, especially to reduce the dependency on fossil fuels energy.[4]

Malaysia is one of the world's largest oil palm producers, producing 47% of the world's supply of palm oil. This is evident through the amount of land dedicated for oil palm tree plantation, in which in 2010, up to 4.5 million hectares of land in Malaysia has been cultivated with oil palm trees, which involved 13.6% of the country's total land area.[5]The palm oil industry generates abundant by-products, and this includes the empty fruit bunch (EFB), palm kernel shell (PKS) and oil palm frond (OPF). Palm oil biomass has great potential as a renewable and cost-effective feedstock[5]as it can be converted to: solid, liquid and gaseous products through processes such as combustion and gasification. EFB is the commonly used biomass due to its availability. The production of one kg of palm oil will produce approximately 4 kg of dry biomass. One third of the oil palm biomass is oil palm EFB and the other two thirds are oil palm trunks and fronds.[6,7] EFB contains neither chemical nor mineral additives, and depending on proper handling operations at the mill, it is free from foreign elements such as gravel, nails, wastes, and wood residues.

Gasification is a matured technology, which was firstly investigated by Thomas Shirley in 1659.[8]It is one of the most effective thermochemical conversion processes for biomass utilization, which produces syngas, a mixture of mainly hydrogen ($H_2$) and carbon monoxide (CO), and other gases such as carbon dioxide ($CO_2$), water ($H_2O$), methane ($CH_4$), higher hydrocarbons ($C_2$+), and nitrogen ($N_2$).[9]Syngas can be used to synthesize liquid fuels, chemicals or to produce heat and power. In gasification reaction, the amount of oxygen is generally one-fifth to one-third of the amount theoretically required for complete combustion.[10]There are three main types of gasifier which are the fixed bed gasifier, fluidized bed gasifier and entrained flow gasifier. Of the three, entrained flow gasifier is the most preferable one as it has relatively short residence time[11]the highest conversion, high-quality syngas and can be used for various feedstocks.[12]The gasification process is performed in the presence of a gasifying agent (for example air, pure oxygen, or steam, or mixtures of these components) at elevated temperatures between 500 and 1400 °C and at atmospheric or elevated pressures up to 33 bar or 480 psi.[13]According to Weiland et al.[14]using the entrained

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flow gasifier for pulverized forest residue gasification should be optimized for temperature slightly above 1400°C in order to decrease the energetic losses to $CH_4$ and $C_6H_6$. This cause the CGE to achieve the value of 70%. The $H_2$/CO ratio was determined to be at range of 0.45–0.61.

Li et al.[15]studied the effects of temperature, steam to biomass ratio (S/B) and biomass particle size on gas composition, gas yield, LHV and hydrogen yield in a fixed bed gasifier. It was reported that when temperature is increased, $H_2$ and $CO_2$ is increased while CO and $CH_4$ were decreased. Similarly, as the temperature increases, the lower heating value (LHV) of the product gas was decreased from 11.26 to 9.13 MJ/Nm$^3$. Franco et al.[16]investigate effect of temperature range by varying S/B ratio on gas yields, energy conversion, gas composition and its higher heating value (HHV) using a fluidized bed gasifier. HHV is defined as is the total energy content released when the fuel is burnt in air, including the latent heat contained in the water vapor and thus it is the maximum amount of energy that are potentially recoverable from a given biomass source.[17]As with the findings of Li et al.[18]the increase in temperature cause the formation of $H_2$ to increase from 26 to 33 mol%, while CO production was declined from 41 to 38%. Lv et al.[19]used a fluidized bed gasifier to investigate the effects of reactor temperature, ER, S/B and biomass particle size. They found that the obtained results indicated that higher temperatures contributed to higher gas yields and increased of the hydrogen production, while other gases were decreased. The carbon conversion efficiency (CCE) was increased from 78.17 to 92.59% with the temperature increase. As the temperature was raised, LHV of the gas reduced from 7.94 to 7.36 kJ/m$^3$. Dillibabu and Natarajan[20]examine the effect of temperature and ER on gas composition and heating value of product gas. The material used was coir pith. From the results, it showed that increased in temperature increases $H_2$ content up to 700°C and then it start to decrease, $CH_4$ increases up to 400°C and decreases due to thermal decomposition of $CH_4$ into $H_2$ and CO. Temperature and ER has no effect on $N_2$ and it remains constant. $H_2O$ decreases with increase in temperature up to 700°C. While CO content increases with an increase in temperature and maximum increase of CO was at 500-700°C corresponds to the decrease of $CO_2$. For the effect of ER, ER has no effect on $H_2$ before 700°C after that it decreases, while $CH_4$ content decreases with increase in ER. Increase in ER increases $H_2O$ content after 700°C indicates the partial oxidation of $H_2$. After 700°C increase in ER decreases CO content corresponding to increase in $CO_2$. Increasing the $H_2$ content in the gas mixture increases the heating value because it has high calorific value.

Zheng et al.[21] has observed that the ratio of $H_2$/CO was noticeably decreasing when ER was increased. At high ER, the production of $CH_4$ and $CO_2$ was low, while the maximum value of the CGE of 75% was obtained at ER value of 0.3. Abdoulmoumine et al.[22]studied the effect of temperature and ER in air gasification using fluidized bed gasifier to determine the product gas distribution. It was found that when the ER is increased, the concentration of CO and $H_2$ increase while $CO_2$ and $CH_4$ decrease. Mohammed et al.[23]using fluidized bed bench scale gasifier investigate effect of temperature, ER, particle size on gas composition and LHV. When ER is increasing, the product gas quality is decreasing due to increasing in oxidation reaction occurred. When ER is varied from 0.15 to 0.35, the $H_2$ content is increased and to maximum value at ER of 0.25 and then decrease as increase in ER, while the $CO_2$ content increased steadily, $CH_4$ and CO is decrease with increase of ER. The LHV of is decreased slightly from 15.38 to 12.35 MJ/m$^3$ as the ER increase.

Many of the previous works on biomass gasification were conducted using either fluidized bed or fixed bed gasifiers, while limited work was done in entrained flow gasifiers. Seeing the potential and the flexibility of this type of gasifier, it is the aim of this work to explore and investigate the effect of operating parameter on gas yield ($H_2$, CO and $CO_2$) using EFB in an entrained flow gasifier. The temperature tested is between 700°C to 900°C while the ER values are varied from 0.2 to 0.4 at atmospheric pressure.

## Materials and Methods

The raw material used in this work, EFB was collected from the Kilang Sawit LCSB Lepar Hilir, Kuantan. Due to its high moisture content of approximately 67%, pre-processing was necessary before the EFB can be used. The samples were washed to remove undesired compounds. They were then manually chopped to smaller pieces and dried in the oven at 100°C for 24 hours. This is to ensure that the moisture content is reduced.[24]The $N_2$ and $O_2$ gas are supplied by Azam Synergy Sdn Bhd with purity of 99% and 98% respectively.

The gasification experiment was performed in a laboratory-scale, operating at atmospheric pressure. Air was used as the gasifying agent, and adjusted according to the desired equivalence ratio (ER) through manual loading. ER may be defined as the oxygen ratio that required for gasification to oxygen required for stoichiometric combustion at given amount of biomass.[25]The furnace is cylindrical shape with an inside diameter of 4.5 cm and the length of 50 cm made of stainless steel which can withstand temperature up to 1100°C. The screw feeder is used to feed through the samples with feeding rate of 1.02 g/s for 20 g samples of EFB. Air enters the furnace in cocurrent flow with the samples along with nitrogen, the carrier gas. The cyclone is used to remove ash and chars from the gas and transfer them into the ash collector which is connected to the bottom of the cyclone. The condenser is used to cool down the hot product gas that passed through it. The gas was collected in an air tight gas bag whose maximum capacity was 1 litre and would fill up every 10 seconds, after which it was replaced with another empty gas bag until the end of the experiment. Each experiment was repeated at least three times and results were in good consistency. The simplified schematic diagram for the experiment is shown in Figure 1.

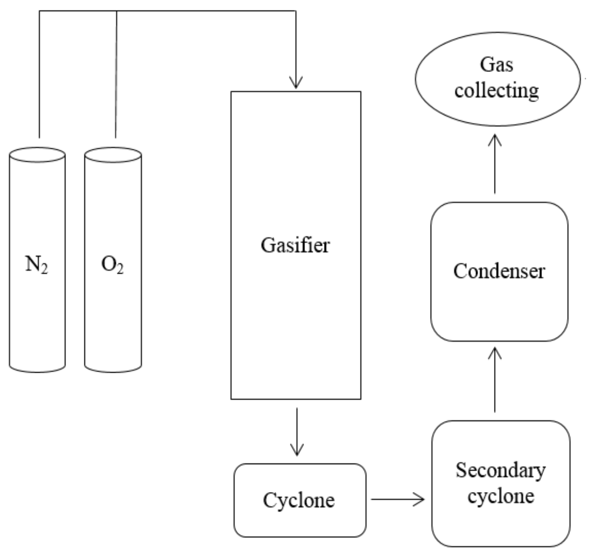



**Figure 1:** Simplified schematic diagram for experiment.

Data recorded from the Thermogravimetric Analyser TGA Q500 is calculated using Equation 1 below to determine the concentration of the gas yield produce.

Example: Concentration $H_2/CO/CO_2$=

$$\frac{Area\ of\ H_2/CO/CO_2}{Total\ Area\ of\ H_2\ /CO/\ CO_2} \quad (1)$$

The parameters that investigated in this research are tabulated in Table 1. Temperature 700°C to 900°C is choose for this research because the range is most suitable range for the gasification process that commonly used by other researchers.[15,19,23]In this work, ER is varied from 0.2 to 0.4 with increment of 0.05 as these ER range also investigate by other researchers.[21,23,26]

**Table 1:** The parameters that investigated in this experiment.

| Temperature (°C) | ER |
|---|---|
| | 0.2 |
| 700 | 0.25 |
| 800 | 0.3 |
| 900 | 0.35 |
| | 0.4 |

## Results and Discussion

The effect of the temperature and ER on the gas yield production is discussed at first. The influenced of CGE on the various temperatures and ER also analyzed subsequently.

### Effect of temperature of gas yield on the production

Figure 2(a) shows the volume percentage of $H_2$ which can be observed that as temperature increase from 700-900°C, the volume percentage of $H_2$ is increased across the ER values tested. The volume percentage for CO and $CO_2$ for different temperature and ER is shown in Figure 2(b) and Figure 2(c) respectively. The CO content is decreasing with increasing of temperature, however the $CO_2$ content is increasing. This can be explained due to the Le Chatelier's principle, in which higher temperatures cause the reactants in exothermic reactions and favor the products in endothermic reactions. So, the reaction of steam reforming $(CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2)$strengthened as temperature increase resulting increase of $H_2$ content.[15,19,27,28]Besides that, the water-gas shift reaction (WGS) reaction $(C + H_2O \leftrightarrow CO + H_2)$ also cause the CO content to decrease as the temperature was increased because the WGS reaction generates $CO_2$, so, as the temperature become higher, it will speed up the reaction rate for $CO_2$ production causing the CO contents to decrease.[15,16,23,27]

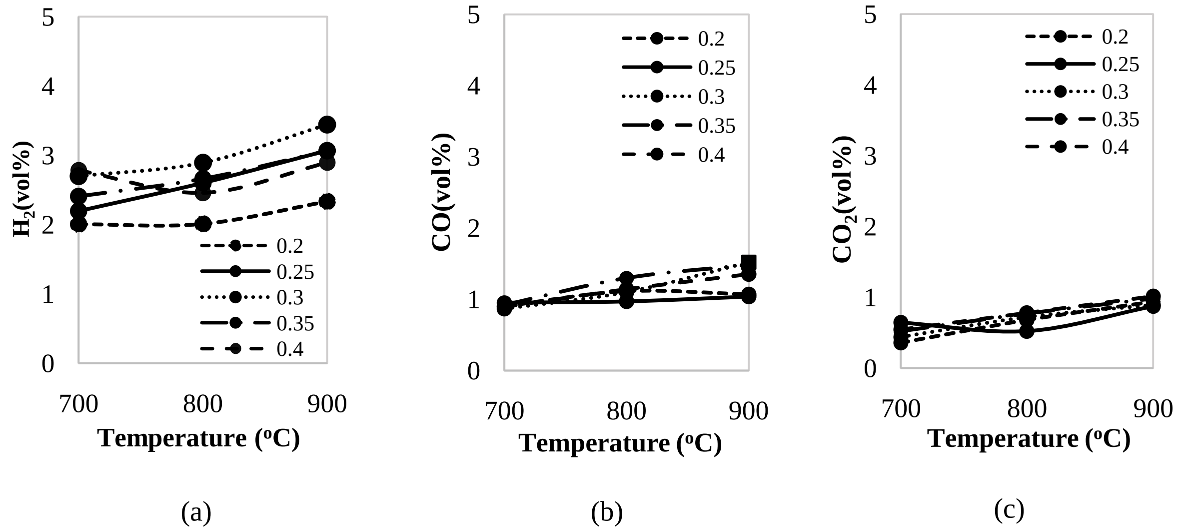



**Figure 2:** The volume % for (a) $H_2$ composition, (b) CO composition, and (c) $CO_2$ composition at different temperature.

## Effect of ER of gas yield on the production

The effect of ER on the gasification of EFB is evaluated at ER between 0.2 and 0.4. The gas yield produced in the experiment is shown in Figure 3(a), Figure 3(b) and Figure 3(c). From Figure 3(a), the $H_2$ content recorded was increased when ER increased but decreased after the ER reached more than 0.3. Figure 3(b) and Figure 3(c) shows the content for CO and $CO_2$ as the ER increased respectively. As the ER increases, the CO content was also increased then decreased meanwhile $CO_2$ content was increased across the ER values.

When ER value was increased, the volume of air supplied into the gasifier was also increased which cause the decreasing of $H_2$ and CO content. This was because when more oxygen is supplied, large amount of $H_2$ and CO were oxidized into $H_2O$, $CO_2$. This phenomenon also cause $CO_2$ to increase as ER is increased.[21,26,29,30] Abdoulmoumine et al.[22] and Mohammed et al.[23]found that when the ER is increased, the concentration $CO_2$ increased due to complete oxidation. When the oxidations of $H_2$ and CO occur, their concentrations of $H_2$ and CO were also decreasing due to its conversion to $H_2O$ and $CO_2$.

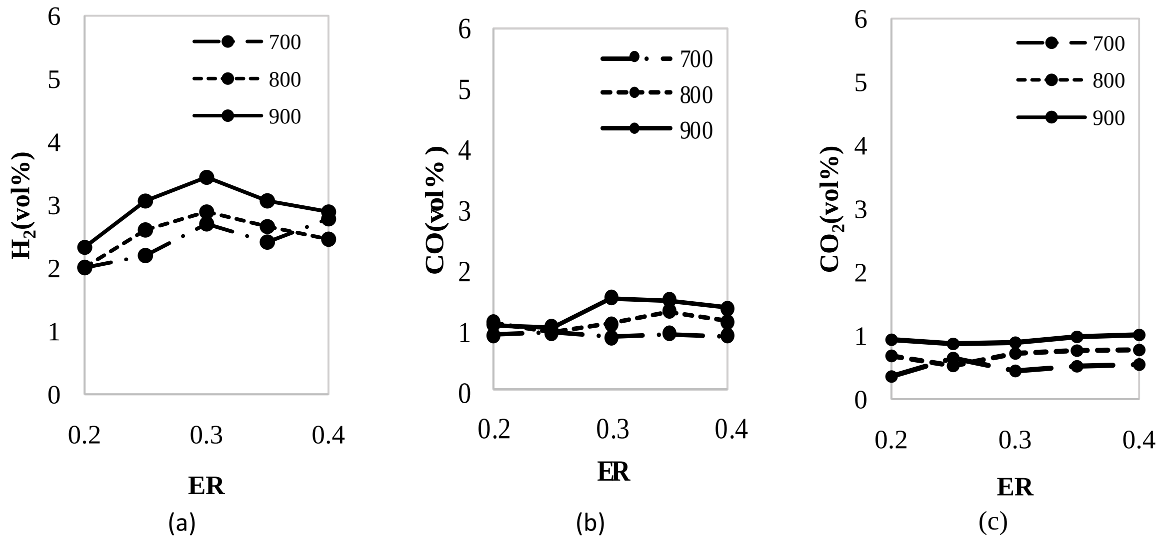
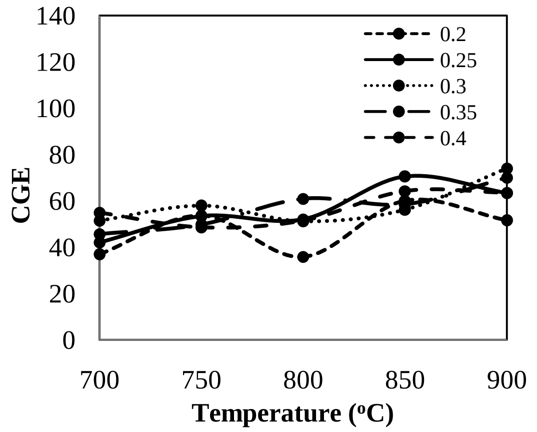


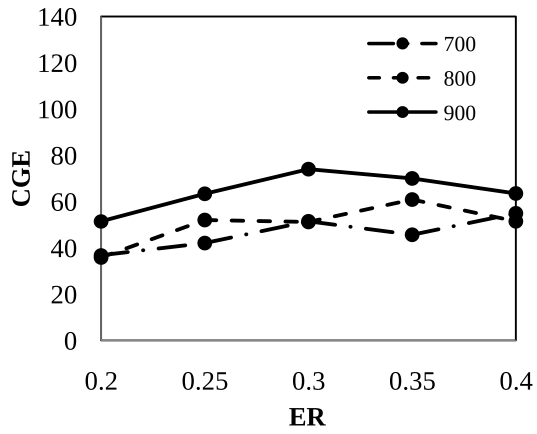

**Figure 3:** The volume % for (a) $H_2$ composition, (b) CO composition, and (c) $CO_2$ composition at different ER.

### Cold Gas Efficiency (CGE) at different temperature and ER

Figure 4(a) is the CGE versus different temperature from 700°C to 900°C with variation of ER. As the temperature increases, the CGE value was also increased. This is due to promotion of the combustion of char by the oxidation and partial oxidation reaction, which promote the pyrolysis reaction of biomass and the gasification reactions of Boudouard and water gas reaction.[31]




(a)




(b)

**Figure 4:** CGE at different (a) temperature, and (b) ER.

Figure 3(b) shows the CGE value at different ER. The most optimum CGE is found at ER = 0.3, after which it decreases with increasing of ER. When ER is increased, the energy conversion will be higher which also mean higher CGE values. However, as ER further increased, the CGE was decreased. This can be attributed that solid biomass used in gasification, there was always unburned carbon in fly ash which cause the decrease of CGE.[21]Similar finding was also reported by Cao et al.[32]who concluded that from the total chemical energy of biomass, 15 – 20% is the chemical energy loss was due to the unburned carbon of fly ash. It is considered that the increase of the supplied air into the gasifier led to the further combustion of the gas and dilution of the gas by the addition of nitrogen in the air, which resulted in the decrease of the HHV of the gas and the cold gas efficiency.[32]

## Conclusion

The gasification of EFB in entrained flow gasifier was studied in the present work. This work showed how the temperature and ER affected the gas yield produce using EFB as feedstock biomass. The maximum CGE recorded is 74% at temperature of 900°C and ER at 0.3. Additionally, at the same temperature and ER, the concentration of syngas ($H_2$ and CO) from in the production gas from gasification of EFB is relatively high. Therefore, from the research, temperature of 900°C and ER 0.3 was found to be able to achieve high product gas yield, and give the maximum CGE.

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