Effect of Equivalent Ratio on Thermal Energy and Exhaust Gas Properties from Gasification of Oil Palm Empty Fruit Bunch using Household Gasifier

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Abstract. This study investigated the effect of equivalent ratio on thermal energy and exhaust gas properties obtained from gasification of oil palm empty fruit bunch by using a household gasifier. The fixed bed household gasifier was designed, fabricated and tested. The chopped oil palm empty fruit bunch (EFB) was used as feedstock and its feeding rate was fixed at 11 kg/hr. The studied equivalent ratios (ERs) of air were 0.1, 0.3, 0.5, 0.7, and 1, respectively. Then, the flame temperature of syngas firing and flue gases properties were determined. The results obtained from study showed that the gasification process was obtained if the ERs were 0.3 and 0.5. When the gasifier was operated at ERs of 0.7 and 1, the process was changed to be combustion. At ER of 0.5, it was the suitable condition for fixed bed gasifier due to this condition provided low ash content, low carbon monoxide, and moderate thermal energy.

1. Introduction
Gasification is one of thermochemical conversion processes which are widely applied for converting solid fuel or biomass into gas fuel, namely producer gas or synthesis gas (syngas). Syngas mainly contains with hydrogen (H₂), carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄), water vapour (H₂O), and nitrogen (N₂) [1, 2]. High quality syngas should contain with high concentration of combustible gases, including H₂, CO and CH₄. The content of non-combustible gases which include H₂O, N₂ and CO₂ should be low. The quality of obtained syngas depends on many factors such as gasifier types, operating conditions, and biomass properties and compositions. The reaction between solid fuel or biomass and air (or oxygen) occurred in gasifier is partial oxidation. The higher oxidation of fuel and air leads to low quality syngas. If the solid fuel or biomass was completely oxidation, the obtained gases will be flue gases, which mostly contain with CO₂, H₂O and N₂ [3]. Gasification process is complex thermochemical process. This is because it involves with many sub-processes, including drying, pyrolysis or devolatilization, combustion or oxidation and gasification or reduction. The operation of gasification process to obtain high quality syngas that has high heating value and low tar content is still challenging.
The fixed bed gasifier [4, 5] is conventional type of gasifiers. There are many types of fixed bed gasifiers classified according to the air flow patterns, for example, up-draft, down-draft and cross-flow [6, 7]. These gasifiers with small scale can be applied for home or household. The advantages and disadvantages of different types of fixed bed gasifiers were summarized by Hina et al [7]. They reported that the main advantages are low cost, easy to design and fabricate, and simple for using. Whereas, the main disadvantages are low feeding capacity, low thermal efficiency, and difficult for scaling up.

However, the small scale household gasifier with updraft pattern as shown in Fig.1(a) is one of simple gasifiers that is widely used for cooking. This gasifier works by combination effect of direct burning mode and gasification mode as shown in Fig.1(b)-1(c). For direct burning mode (Fig.1(b)), the air with sufficient amount for complete combustion is supplied into combustion zone at the bottom of gasifier (or bottom zone) and then it interacts with fuel for combustion with specific zone. In the part of gasification mode (Fig.1(c)), the air with insufficient amount for complete combustion enters to the gasifier at the same position, but the amount of this air is not enough for complete combustion. Thus, the obtained heat is used to generate the producer gas or synthesis gas “syngas”. The syngas flows to gasification zone through small lateral by passing a small holes and then it enters to small upper holes. Finally, the syngas is burned by complete combustion at the top of the stove.

![Image of household gasifier](image-url)

**Figure 1.** Household gasifier for cooking stove

Generally, the feedstock or solid fuel for using with household gasifier stove should be small size. If the firewood is used, its size should be 5 – 10 cm in length, and 5 cm x 5 cm in cross-section. For this study, the oil palm empty fruit bunches were used as feedstock. Both direct burning and gasification were operated under specific conditions to observe the combustion characteristics and flue gas properties. The main objective is therefore to study the effects of equivalent ratios on thermal energy and exhaust gas properties of a household gasifier stove that used oil palm empty fruit bunches as feedstock. The temperature at combustion zone, ash content after finishing process, carbon monoxide in produced gases, and thermal energy are determined.

2. **Experimental setup and procedure**

2.1. **Setup of gasifier system**

The diagram of experimental setup of the fixed bed gasifier is shown in Fig 2. The reactor was divided into 2 components, including housing and reactor. The diameter of housing (D_H) was 40 cm, and the total height (H_H) was 50 cm. In the part of reactor, the diameter of reactor (D_R) was 26 cm, and the total height from the bottom to the top (H_R) was 40 cm. The surface of the reactor was drilled into small
holes. It is designed for the syngas flows to gasification zone through small lateral by passing small holes and then it enters to small upper holes.

The air supplied by the blower (blue line) was fed into the gasifier via the pipe. Before it flows to the gasifier, the flow rate was calibrated by orifice flow meter. The flow rate of inlet air was controlled by adjusting blower blade revolution using an inverter. The air was flowed to the reactor through the bottom of housing and then it flowed to the reaction zone by passing the holes under reactor. The feedstock of oil palm empty fruit bunch was fed into chamber by using a screw conveyor which can be controlled mass feed rate. The speed of feeder was adjusted by changing the speed of motor which was equipped with an inverter. The investigated equivalent ratios of the air were 0.1, 0.3, 0.5, 0.7, and 1. The four steps of gasification process was used to convert air and feedstock into the syngas (Red line) which was combustible at the top of gasifier. Thus, at inside the reactor the reaction of biomass burning at combustion zone and syngas firing at above zone (Black line) were occurred simultaneously. Then, the flue gas leaving from stove was considered as exhaust gas.

**Figure 2.** Schematic diagram of fixed bed gasifier for cooking stove

The thermal energy (q) [8] obtained from syngas firing was transferred to boiler for considering the energy transfer and thermal efficiency. The obtained energy can be evaluated by $q = mC_p \Delta T$, where $m$ is mass of water (kg), $C_p$ is specific heat capacity of water (kJ/kg·°C), and $\Delta T$ is temperature difference (°C).

The water boiler was placed at the above of the stove. The distance between the top of the stove and bottom of boiler was 7 cm. The water in boiler was boiled for 20 minutes for all experiments. The mass of water filled in boiler was fixed at 15 kg for each experiment. After syngas firing, the temperature difference was measured and recorded by data logger.

The temperature at combustion zone and syngas firing zone was measured by S-types thermocouples. The temperature of water inside boiler was measured by K-type thermocouple. They were equipped at the center of reactor with appropriate position as shows in Figure 2. The carbon monoxide in fuel gas was measured by flue gas analyzer (Testo 300). The sample was collected after burning for 20, and 40 min, respectively.
2.2 Feedstock preparation

The feedstock used in this study was oil palm empty fruit bunches which were taken from palm oil milling factory. The sample of oil palm empty fruit bunches is shown in Fig 3(a). The bunches were chopped to reduce the size. The circumference of their size was less than 5 cm and a length was not longer than 20 cm as shown in Fig 3(b). The moisture content of prepared sample was lower than 15%. The determined properties of feedstock were shown in Table 1. This feedstock has the high amount of volatile matter, carbon content and hydrogen content in order to help the combustion process going to direct combustion or gasification according to varied equivalent ratio [9].

![Oil palm empty fruit bunches](image1)
![Chopped oil palm empty fruit bunches](image2)

**Figure 3.** Photo of oil palm empty fruit bunches

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**Figure 3.** Photo of oil palm empty fruit bunches

| Table 1. Properties of oil palm empty fruit bunch [10] |
|-------------------------------------------------------|
| Properties                                           | Value   |
| Ultimate analysis (wt.%, dry basis)                  |         |
| Carbon                                               | 40.7    |
| Hydrogen                                             | 5.4     |
| Nitrogen                                             | 0.3     |
| Oxygen                                               | 47.8    |
| Sulfur                                               | 1.2     |
| Proximate analysis (wt.%, dry basis)                 |         |
| Fixed carbon content                                 | 27.9    |
| Volatile matter                                      | 67.5    |
| Ash content                                          | 4.6     |

2.3 Experimental parameter

In order to study the effect of ER on the temperature of combustion zone and syngas firing zone, and flue gas properties, the feeding rate of feedstock was fixed at 11 kg/hour, and the mass flow rate of the air was varied according to equivalent ratio (ER) at 0.1, 0.3, 0.5, 0.7, and 1, respectively. The inlet air velocity according to different equivalent ratios is shown in Table 2.

| Table 2. Experimental parameter                      |
|------------------------------------------------------|
| Equivalent Ratio (ER) | Velocity of air inlet (m/s) |
| 0.1                   | 0.68                      |
| 0.3                   | 2.03                      |
| 0.5                   | 3.39                      |
| 0.7                   | 4.74                      |
| 1.0                   | 6.78                      |
3. Results and discussion

3.1. Visual observation of flame during combustion process and gasification process

The pattern of flame during direct combustion and syngas firing from gasification process is shown in Fig. 4(a) and 4(b). As shown in Fig. 4(a), it can be seen that the flame from direct combustion was occurred at bottom of reaction chamber and it moved upward. The flame tip was relatively high as compared to the top surface of the stove. The flame colour from direct combustion was also clearly different from syngas firing flame colour. This is due to the difference in flame temperature, and flame compositions. For direct combustion, the flame is occurred by firing of fixed carbon and volatile matter. Consequently, the flame colour is orange-red as shown in Fig. 4(a). In the case of flame from syngas firing as shown in Fig. 4(b), the flame was occurred at top of stove due to the firing of syngas from top hole. The pattern of the flames started from the sides and then it converged at the middle of stove before moving upwards. The flame colour of syngas firing was different from direct combustion of biomass due to the syngas contains with combustible gases such as CO, H\(_2\) and CH\(_4\).

Thus, the process that occurred in Fig. 4(b) can be defined as gasification process, which was consistent with the flame pattern and flame colour of combustible syngas. The obtained result also showed that the ER ranging from 0.1 to 0.5 provided the gasification process. At ER higher than 0.5, the process will be more combustion, which can be observed from flame pattern and flame color.

![Flame pattern and colour](image)

(a) Flame pattern from direct combustion at ER = 1  (b) flame from gasification at ER = 0.5

**Figure 4.** Photo of flames pattern and colour from direct combustion and syngas firing
3.2. The effect of equivalent ratio on temperature of combustion zone and flame zone

Figure 5 shows the effect of equivalent ratios on the temperature of combustion zone inside the stove and flame zone above the stove. The result show that operation of stove at ER of 1 led to the highest temperature. The reduction of ER from 0.7 to 0.1 led to lower temperature at both combustion zone and flame zone. This is because at ER of 1 the reaction inside the stove was completely combustion, following the stoichiometric combustion theory. Consequently, the heat of formation from combustion elements (C, H and S) was highest, leading to high temperature at each zone. In addition, the inlet air velocity was also high at ER of 1, thus the turbulent of the air inside stove or combustion zone help to enhance the combustion quality. In contrast, at ER of 0.1 the air was low for generating heat at combustion zone, consequently the combustion rate was also low, which led to low temperature in combustion zone and flame zone. For gasification process, the partial oxidation of biomass with air strongly depends on the ER. At suitable ER, the syngas quality will be best both compositions and energy content.

At ER=0.5, the temperature of both combustion zone and flame zone dropped which was lower than ER=0.3 and 0.7. It can be explained that it was in transition process of gasification to direct combustion. Based on the obtained results from visual observation and temperature measurement, at ER of 0.7 and 1, the pathway of process was mostly combustion. The direct combustion of biomass sample that led to high temperature at these ERs can be also observed from syngas firing. The flue gas or producer gas in this case has low concentration of combustible gases, leading to no firing of that gas. The experiment at these ERs also provided great amount of smoke leaving from the stove. At ER of 0.1 - 0.5, the amount of air is suitable for gasification process, resulting in non-complete combustion and providing more combustible syngas properties. However, from the observation at ER of 0.1 the producer gas cannot be combusted continuously, because of low reaction rate between feedstock and air, resulting in clogging of flow in the reactor which causes the reactor shutting down.

![Figure 5. Effect of ERs on temperature of combustion and flame zones.](image)

The effect of equivalent ratios on remaining ash (at the bottom of gasifier stove) is shown in Figure 6. The results indicated that the ER had effect on the remaining ash of gasifier. Operation of gasifier at ER of 1.0 provided the highest amount of ash content (15 %). When the ER was reduced, the remaining ash was lower such in the case of ER of 0.7 and 0.5. The lower ash content may be due to the reaction during the gasification process. At ER of 0.7 and 1, the process was direct combustion which is fast oxidation of biomass and air, leading to has some incomplete reaction of solid fuel (biomass) and air on fixed bed reactor. Consequently, the ash content was high. In contrast, at ER of 0.5 the process was gasification which the reactor was slower that combustion, thus most of biomass was converted as ash. When the ER was lower than 0.5, the reaction was lower and then the ash content was increased. The finding is in similar to that of Upadhyay et.al. [11]. For gasification process, the gasifier should be
operated at suitable ER to obtain good quality syngas, as well as low remaining ash content. This is because ash is considered as waste, it needs to be appropriate management or utilization.

Figure 6. Effect of equivalent ratios on remaining ash.

Figure 7. Effect of equivalent ratios on carbon monoxide of flue gas or producer gas.

Figure 7 shows the effect of equivalent ratios on the carbon monoxide (CO) content in flue gas or producer gas. The CO content was measured at position that was above the reactor of 30 cm. The result showed that CO content results can be divide into 2 groups. First one, high carbon monoxide which was higher than 3000 ppm, these results were obtained when gasifier was operated at ER = 0.7 and ER = 1. At these ERs, the process was direct combustion, thus the flue gas will not be re-burned again. For the second group, the results obtained from ER = 0.5, and ER = 0.3. This group was low carbon monoxide content which was lower than 3000 ppm. This is because the syngas was re-burned to be flue gas. Consequently, the carbon monoxide was eliminated during re-burning process. At ER = 0.1, it had the lowest carbon monoxide content. This result was consistent with the result of temperature in combustion zone.

3.3. Thermal energy obtained from gasifier stove

The thermal energy was measured by determining the heat transfer from reactor to water inside container which was controlled the condition for all experiments. The thermal energy from varying the equivalent ratio is shown in the Fig. 8. It is seen that the maximum of thermal energy was obtained when the gasifier was operated at ER of 0.7, following by ER of 1.0 and 0.5. At ER of 0.1, the thermal energy was lowest.
which is not suitable for operating fixed bed gasifier. It should be noted that ER of 1.0 and 0.7 had high carbon monoxide of flue gas which will be effect on environmental impact. So, the suggested operating condition is ER=3.0 - 0.5 due to having moderate thermal energy and low carbon monoxide.

4. Conclusion
This study investigated the effect of equivalent ratio on thermal energy and exhaust gas properties obtained from gasification of oil palm empty fruit bunch by using a fixed bed household gasifier stove. Based on the obtained result, it can be concluded that:

(1) The fixed bed gasifier stove should be operated at ER of 0.3-0.5 for gasification process. At ER of 0.7-1, the process was moved to combustion.

(2) The temperature at combustion zone and from zone depended on ER and process reaction. At ER = 0.5-0.7, the amount of remaining ash was lower than 10 %. Operating of gasifier at ER of 0.3-0.5 led to obtain syngas with low carbon monoxide.

(3) The highest thermal energy was obtained when the ER was 0.7, following by ER = 0.1 and 0.5. These results indicated that operation of gasifier stove at ER of 0.5 provided the good condition for household utilization and applications, particularly for cooking.

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