Combustion Characteristics of Palm Kernel Shell Mixed with Crude Glycerol Briquette Fuel

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Abstract. The purpose of this research was to study the combustion characteristics of palm kernel shell (PKS) mixed with crude glycerol. Initial supplied air and ratios of glycerol were varied for best combustion to obtain high temperature, high combustion rate and minimum emission. PKS is mixed with molasses and crude glycerol at 3 different ratios by mass i.e. 90:10:0, 85:10:5, 80:10:10 (PKS: molasses: crude glycerol). Mixed material was compressed at 10 MPa in a designed hydraulic briquettizer. Then the briquette was burnt with different supplied airs corresponding to 600%, 750%, 900% and 1050% theoretical air. The results show that when crude glycerol and supplied air were increased, the temperatures and rates of combustion increased to a maximum value and dropped. For exhaust gasses analysis, Carbon monoxide (CO), Nitrogen dioxide (NO$_2$), Sulfur dioxide (SO$_2$) and Acrolein gas were all within Standards. Therefore, it can be concluded that PKS mixed with crude glycerol at 85:10:5 and theoretical air of 900% provide the best combustion and is recommended for use as briquette fuel.

Introduction

Nowadays energy is very important for the existence of mankind and the demand keeps rising. The main sources of supply are from fossil fuel causing environmental problems. Therefore, the development of alternative fuel with similar properties to replace fossil fuel is interesting. One of promising alternative fuel is the use of biomass fuel from agricultural waste. Therefore, in this research palm kernel shell (PKS) will be used as raw material to produce biomass briquette. PKS is a waste from the production of palm oil. Data from Food and Agriculture Organization of the United Nations (FAO) found that in the year 2009 palm oil of 45 million tons were produced and generated 10 million tons of PKS as waste [1]. In 2016, Thailand produced 11 million tons of palm oil [2] and expected 2.4 million tons of PKS. It was reported that PKS has a heating value of 21.54 MJ/kg (6% moisture content), high carbon composition (50% by mass) and ease of stocking and transportation [3]. Therefore, PKS is of interest to be used as biomass briquette fuel. In this research, PKS was mixed with crude glycerol and molasses in various combinations and then densified to be briquette fuel. A combustion chamber was designed and constructed to investigate the combustion characteristics of the briquettes. Supplied air for combustion was varied to find an optimum air giving high combustion temperature, high combustion rate and the exhaust gases within standards. This can make ultimate use of PKS as energy for palm oil industry in the future.

Materials and Methods

Sample Characterizations

PKS used in this research is a waste from palm oil production. For one fresh palm bunch (by weight) comprises 21% oil palm, 6-7% palm kernel, 14-15% fiber, 6-7% PKS and 23% empty fruit bunches [1]. The PKS will be crushed and grind to 10 mm or smaller and then well mixed with molasses (binders) and crude glycerol at the following ratios by mass of 90:10:0, 85:10:5 and 80:10:10
PKS:molasses:crude glycerol) then compressed in a hydraulic briquettizer at 10 MPa for 3 minutes. A briquette has 52 mm diameter, 42 mm in length and the average mass of 100 g. Then it was sun-dried as shown in Figure 1a. From the data above, the density of the briquette is 1,121.70 kg/m³. The proximate and ultimate analysis of palm kernel shell are shown in Table 1.

![Figure 1. (a) Palm kernel shell briquette, (b) crude glycerol and (c) molasses.](image)

Table 1. Proximate and Ultimate analysis of PKS [4].

<table>
<thead>
<tr>
<th>Physical and chemical characteristics</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>%</td>
<td>2.88</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>%</td>
<td>10.85</td>
</tr>
<tr>
<td>Volatiles</td>
<td>%</td>
<td>84.86</td>
</tr>
<tr>
<td>Ash</td>
<td>%</td>
<td>4.29</td>
</tr>
<tr>
<td>Carbon (C)</td>
<td>%</td>
<td>46.53</td>
</tr>
<tr>
<td>Hydrogen (H₂)</td>
<td>%</td>
<td>5.85</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>%</td>
<td>0.89</td>
</tr>
<tr>
<td>Sulfur (S)</td>
<td>%</td>
<td>0</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>%</td>
<td>42.32</td>
</tr>
<tr>
<td>Higher heating value (HHV)</td>
<td>MJ/kg</td>
<td>18.81</td>
</tr>
</tbody>
</table>

Crude glycerol is a by-product of biodiesel production having dark brown colour (Figure. 1b). Its fire point is 204°C, boiling point 290°C, dynamic viscosity 1 Pa s which can be dissolved in water and methanol [5]. Crude glycerol is a good renewable energy source for various applications which might be due to high carbon content. For this research, crude glycerol will be mixed directly with PKS.

Molasses is a viscous fluid with black-brown colour as shown in Figure. 1c. It is a by-product of sugar production. The composition of molasses comprises 20% water, 35% sucrose, 9% fructose, 7% glucose, 12% ash and some other carbohydrates, nitrogen, acids, vitamin, wax and several minerals [6]. It is used as a binder of the briquette fuel [7].

**Analysis of Air Flow for the Combustion of PKS Mixed with Crude Glycerol Briquette**

From the ultimate analysis of PKS (Table 1) combustion equation for 100 g of briquette with 100% theoretical air, can be written in Eq. 1.

\[
(3.878C + 2.925H_2 + 1.323O_2 + 0.032N_2 + 0.000S + 0.160H_2O) + 4.018(O_2 + 3.76N_2) + \text{Ash} \\
\longrightarrow 3.878\text{CO}_2 + 3.085\text{H}_2\text{O} + 15.140\text{N}_2 + 0.000\text{SO}_2 + \text{Ash} \tag{1}
\]

Similarly, for 1 mole of crude glycerol and molasses with 100% theoretical air combustion equation are shown in Eq. 2 and Eq. 3.

\[
C_3H_8O_3 + 3.5(O_2 + 3.76N_2) \longrightarrow 3\text{CO}_2 + 4\text{H}_2\text{O} + 13.16\text{N}_2 \tag{2}
\]

\[
C_{12}H_{22}O_{11} + 12(O_2 + 3.76N_2) \longrightarrow 12\text{CO}_2 + 11\text{H}_2\text{O} + 45.12\text{N}_2 \tag{3}
\]
When PKS, crude glycerol and molasses were mixed in different ratios, total supplied air required for combustion a mixed briquette can be determined by taking air ratio corresponding to material ratio. Therefore, the air flow rates for combustion the briquettes of 90:10:0, 85:10:5 and 80:10:10 mixing ratio can be calculated to be 1.44 m$^3$/h, 1.43 m$^3$/h and 1.42 m$^3$/h respectively for 40 minutes complete combustion. For example, 85% of PKS, 10% of molasses, 5% of crude glycerol required 1.23 m$^3$/h, 0.14 m$^3$/h and 0.06 m$^3$/h respectively. So total supplied air is $1.23 + 0.14 + 0.06 = 1.43$ m$^3$/h.

Normally the initial theoretical air should be between 150-250% with briquette density range between 400-700 kg/m$^3$ [7-8]. For the PKS mixed with crude glycerol briquette having a density of 1,121.70 kg/m$^3$, it would require supplied air more than the above recommendation. Initially, it was found that the initial theoretical air from 150 to 450% the briquette fuel was burned but did not last long and stop burning because the density of briquette fuel was too high. Then initial theoretical air of 600%, 750%, 900% and 1050% were used. Based on 40 minutes of complete combustion, air flow rates corresponding to each case are shown in Table 2.

<table>
<thead>
<tr>
<th>PKS : molasses : crude glycerol</th>
<th>Air flow rates supplied used for combustion in 40 minutes (m$^3$/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio by mass</td>
<td>100%</td>
</tr>
<tr>
<td>90:10:0</td>
<td>1.44</td>
</tr>
<tr>
<td>85:10:5</td>
<td>1.43</td>
</tr>
<tr>
<td>80:10:10</td>
<td>1.42</td>
</tr>
</tbody>
</table>

Combustion of PKS Briquettes and Measurements

The constructed chamber with internal dimensions of 230 mm x 230 mm x 230 mm made from 76 mm thick fire-resistant brick wall covered with 3 mm steel sheet was used to burn PKS briquettes illustrated in Figure. 2 [9]. The briquette of 200 g was burnt with the initial theoretical air of 600%, 750%, 900% and 1050% respectively. Based on 40 minutes complete combustion tests were carried out with 3 replicates of each case. Air flow rate was set to the required flow using flow meter (Testo 435). The briquette was initially ignited outside the oven and then put into the chamber. The temperatures were measured by 6 K-type thermocouples (Figure. 2). The temperatures were recorded using data logger every 20 seconds. Load cell (S-type) connected to the tray was used for measuring a mass of the briquette during combustion. The mass converter is connected to the computer monitor and recorded data every second. The flue gases such as Oxygen ($O_2$), Carbon monoxide (CO), Carbon dioxide ($CO_2$), Nitrogen dioxide ($NO_2$), Sulfur dioxide ($SO_2$) and Hydrocarbon (HC) were measured by gas analyzer at the exit of the exhaust chimney. Measurement of Acrolein gas was done under National Institute for Occupational Safety and Health, NIOSH 2539 standard and using sorbent tubes air sampling. After that, Acrolein gas was quantified directly in Gas Chromatography-Flame Ionization Detector (GC-FID).
Results and Discussions

Combustion of PKS mixed with crude glycerol briquettes (0%, 5% and 10% crude glycerol by mass) for 4 different supplied airs (600%, 750%, 900% and 1050% theoretical air) were studied.

Combustion Temperature of PKS Briquettes

Temperature sensors were placed in the combustion chamber as mentioned earlier. The temperatures were recorded every 20 seconds using a Data logger. Then, averaged temperatures were presented as the representative shown in Figure 3a.

From Figure 3a, it is found that the combustion temperature increased with supplied air and reached a maximum. Over supply of air can then decrease the temperature. Because of the fresh air was at lower temperature and rich nitrogen promotes the Endothermic reaction which resulted in decreasing the temperature in the oven [10]. Similarly, the increase of crude glycerol increased the temperature. The maximum temperature of 599.60ºC can be obtained in the case of 900% initial theoretical air and 5% crude glycerol.

Combustion Rate of PKS Briquette

During combustion of a PKS briquette, mass of the briquette was monitored every 1 second. Figure 3b shows the mass change during burning. Then, the combustion rate can be calculated using the slope of the graph at the point where the mass reduced to 50% (100 g) as shown in Figure 3b. The combustion rate selected to present in Figure 3a. The combustion rate was increased when airflow...
and crude glycerol mixing ratio increased since crude glycerol promotes the ease of burning. In addition, more air supply can endorse the burning of the briquette but too much air can lead to a lower rate of combustion which corresponds to Wang et al. [11]. The results showed that the briquette with 5% crude glycerol and 900% theoretical air gives the highest combustion rate of 0.18 g/s.

**Flue Gases Analysis**

The flue gases analysis was performed using Testo 350 gas analyzer at the exit of the exhaust chimney. Since we were interested in the highest combustion rate and also highest temperature, then, only 5% crude glycerol mixed briquettes burning at 900% theoretical air was tested. When the steady state combustion was reached at the 10th minute, the gases were sampled thrice and data were recorded and averaged. By compared with the standards of Commission Regulation (EU) 2015/1185 and Directive (EU) 2015/2193, limited values for the pollutants which are directly relevant to biomass emissions are shown in Table 3.

<table>
<thead>
<tr>
<th>Emission (mg/m$^3$)</th>
<th>Standards</th>
<th>PKS briquettes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>1,500$^a$</td>
<td>606.0</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>300$^b$</td>
<td>4.3</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>200$^b$</td>
<td>0.0</td>
</tr>
<tr>
<td>HC</td>
<td>(No limited)</td>
<td>271.3</td>
</tr>
<tr>
<td>O$_2$ (%)</td>
<td>(No limited)</td>
<td>20.7</td>
</tr>
<tr>
<td>CO$_2$ (%)</td>
<td>(No limited)</td>
<td>1.0</td>
</tr>
</tbody>
</table>

$^a$ European Commissin (EC), $^b$ European Parliament (EP)

From Table 3, the PKS briquette emitted exhaust gases of CO = 606.0 mg/m$^3$, NO$_2$ = 4.3 mg/m$^3$, SO$_2$ = 0.0 mg/m$^3$, HC = 271.3 mg/m$^3$, O$_2$ = 20.7% and CO$_2$ = 1.0%. They are all within standards for flue gas required.

**Acrolein Gas Analysis**

Furthermore, Acrolein gas analysis was made by using GC-FID for only 5% crude glycerol mixed briquettes burning at 900% theoretical air case. The sample of exhaust gas was tapped into sampling tubes and sent for GC-FID analysis. Results were compared with Safety Standards. It is reported that human should not inhale this Acrolein gas more than 0.3 ppm [12]. In addition, combustion of crude glycerol is likely to emit Acrolein gas. This unstable and toxic carbonyl compound is the result of the thermal decomposition of crude glycerol and can be formed at temperatures around 280°C with very high toxicity even at low concentrations (2 ppm) [13]. The test results showed Acrolein gas at the 11.868 minute peak as depicted in Figure. 4. The interpretation of the data showed that 5 ppm of Acrolein was formed during combustion of the briquette which was higher than Safety Standards. However, this is because Acrolein gas was measured in the exhaust chimney before the exhaust gas exposed to the environment. If the measurement is taken place at an open space outside the exhaust chimney, the concentration would be expected to be less than 1,000 times due to a very large volume of space. This can be concluded that when flue gases expose into open air space, Acrolein gas concentration is within safety standard.
Conclusion

The purpose of this research was to study the combustion characteristics of palm kernel shell (PKS) mixed with molasse and crude glycerol. PKS is mixed with molasse and crude glycerol at 3 different ratios by mass of 90:10:0, 85:10:5, 80:10:10 (PKS:molasses:crude glycerol). The combustion of briquettes was carried out with supplied air corresponding to the theoretical air of 600%, 750%, 900% and 1050%. It is found that the combustion rate and temperature increased with increasing supplied air and % of glycerol. However, too much air supplied to the chamber decreased both combustion rate and temperature. Thus, it can be concluded that the supplied air and ratio of crude glycerol affected the combustion of PKS briquettes. The results showed that the PKS briquette of ratio 85:10:5 and 900% theoretical air can give the highest temperature and combustion rate of 599.60ºC and 0.18 g/s respectively. Exhaust gases were also analyzed and found to be within standards.

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References


