INVESTIGATION OF STAGED AIR SUPPLY ON GRATE COMBUSTION OF PALM KERNEL SHELL MIXED WITH SELECTED ADDITIVES (AL₂O₃ AND CaO)

K. O. Oladosu, E. O. Olafimihan, K. A. Babatunde, B. Kareem and A. A. Mustapha

1,2 Dept. of Mechanical Engineering Ladoke Akintola University of Technology, Ogbomoso, Nigeria
3 Dept. of Chemical Engineering Ladoke Akintola University of Technology, Ogbomoso, Nigeria
4 Dept. of Mechanical Engineering Federal University of Technology Akure, Ondo State, Nigeria

ABSTRACT
Grate furnace is a proven technology for combustion of biomass for heat and power generations because of its fuel adaptability and easy handling. Carbon monoxide, carbon dioxide and temperature measurement are the key performance indices of the grate furnace for energy generation. This study aimed at investigating the influence of adjusting primary to secondary air supply on combustion efficiency and gaseous emission. The results of experimental work showed that temperature above grate decreases as the primary to secondary air setting increases. Maximum combustion temperature recorded in this study was 785°C above the grate during the test period at air split ratio of (40:60). At the exhaust port (1.38 m) above the grate [the freeboard temperature region increases in 60 minutes of combustion] maximum level of CO, (8446 ppm) accompanied by low level of CO (285 ppm) was recorded. These optimality attainments have made the air ratio (out of the test cases) most appropriate for efficient combustion.

Correspondence: kooladosu@lauetech.edu.ng, coolafimihan@lauetech.edu.ng, bkareem@futa.edu.ng, akeemmustapha19@gmail.com

1.0 INTRODUCTION
Biomass is considered to be one of the key renewable resources which play an important role in sustenance of energy which are largely needed for industrial use (Sulaiman et al., 2011). In many industries where agricultural products are being processed, it has been common practice to use organic waste as fuel for production of the energy needed for the processing (Najmi and Rosli, 2006). Palm fruit is one of the key agricultural crops found in southern and northern part of Nigeria. Wastes from palm fruit serve as biomass from which energy can be generated. Palm Kernel shells (PKS) are carbonaceous solids, produced from the processing of palm oil fruit. It contains high volume percentage of carbon element and may be converted as a heat energy source by thermal reaction of the carbon content. PKS is commonly used in combustion processes, especially at oil mills as boiler fuel to generate heat and electricity (Edmund et al., 2014).

There are varieties of ways by which PKS can be burnt in order to free the locked up energy element confined within it. Technologies used by oil palm mill to generate enough energy for its consumption are fixed bed (1 kW- 50 MW), fluidized bed (5 MW-
100 MW) and dust technology (10 MW- 500 MW). Efficiencies of these technologies are dependent on fuel properties and the mixing quality between flue gas and combustion air (Sjaak and Jaap, 2008). Pitchet and Vladmir (2014) recorded high combustion efficiency and low emission performance in a fluidized bed combustion of palm kernel shell using optimized particle size, although the start up and running cost of operation associated with this technique make it difficult to be operated by small scale business. Grate furnace combustion is a widely used conversion method to obtain heat and power from biomass. However, grate firing is yet to be further developed in terms of higher combustion efficiency and lower emission (Yin et al., 2008). Remarkable improvement has also been recorded on design of large scale grate furnaces (fixed bed), yet additional work need to be done in small scale businesses in term of poor mixing especially when co-firing different fuel and high moisture fuel content for improve combustion and reduction of ash deposition on components of grate furnace (Najmi et al., 2007). Grate furnace tolerates wide range of fuel type and high combustion efficiency is attained due to reduction in blockages by positive movement of fuel down grates and well controlled air distribution (Thomas et al., 2009).

In addition, the use of additive mixed with solid wastes can significantly reduce alkaline metals deposition on the surface of tubes (Liang, 2014). This will enhance combustion process and decrease ash deposition. In this paper, we aimed at investigating the effect of primary to secondary air ratio on combustion of palm kernel shell additive mixture in a pilot scale grate furnace.

2.0 MATERIALS AND METHODS

2.1 Material Collection and Preparations

Palm kernel shells were obtained from a local palm oil mill in Ogbomoso. The preparation of the shells was done by crushing them into smaller pieces using granulator (SG-16 Series) SHINI Plastic Technologies obtained from China and further reducing the sizes with blender. This was followed by sieving the dried blended PKS to particle sizes (1 - 7 mm). Two additives (Al₂O₃ and CaO) of analytical grades were obtained from reliable representative in Nigeria. Al₂O₃ with constituents; Chloride (Cl), Sulfate (SO₄), arsenic, calcium, copper, iron, lead and potassium having particle size 100-325 mesh) was obtained from LOBA Chemic-laboratory reagent and fine chemicals India. The Calcium Oxide (CaO) was in a powdery form with HCl 0.1%, Chloride (Cl) 0.05% Sulfate (SO₄) 0.5% and heavy metals (Pb) 0.05% were the constituents). The equipment used include the air flow metre, Spectrophotometer, 12 points temperature channels recorder, air quality metre, muffle furnace, Gallenkamp Bomb Calorimeter and other laboratory facilities.

2.2 Experimental set up and Procedure

A furnace with grate assembly was used for the experiment. The furnace had a cylindrical section as its body with an internal diameter of 600 mm and having a combustion volume of approximately 4.056

2.3 Calculation of Combustion Efficiency

The combustion efficiency according to Nussbaumer and Good (1998) is given by Eq1:

\[
\eta_c = 100 - \frac{L_{\text{thermal}}}{L_{\text{chemical}}}
\]

where; \( \eta_c \) is Combustion efficiency,

\( L_{\text{Thermal}} \) is Thermal losses by sensible heat of

\( \text{flue gas} \) and \( L_{\text{chemical}} \) is Chemical losses by incomplete combustion

Investigation of Staged Air Supply on Grate Combustion of Palm Kernel Shell Mixed With Selected Additives (Al₂O₃ and CaO)
\( L_{\text{thermal}} \) and \( L_{\text{chemical}} \) are given by equation

\[
L_{\text{thermal}} = \frac{(T_g - T_a)[1.39 + \frac{122}{100} - \frac{0.2442}{100} - 0.02]}{LHV} \quad [\%] \tag{2}
\]

\[
L_{\text{chemical}} = \frac{CO}{CO_2 + CO} \left( \frac{11800}{LHV - 0.2442} \right) \quad [\%] \tag{3}
\]

where; \( T_g \) = Temperature of flue gas, \( T_a \) = Temperature of air and \( LHV \) = Lower Heating value

3.0 RESULTS AND DISCUSSION

3.1 Temperature profile

Parameters and combustion properties at different ratio of primary to secondary air supply are shown in Table 2 and Table 3. The temperatures were measured at five different locations in the combustor; above the grate \( (h_a=0.3 \text{ m}) \), at the core of the furnace \( (h_c=0.7 \text{ m}) \), at the steam collection header \( (h_s=1.0 \text{ m}) \), superheater region \( (h_u=1.3 \text{ m}) \), and at the exhaust port \( (h_e=1.38 \text{ m}) \). In all the tests, because of fuel and heating process, the combustion temperature decreases only at the time immediately following the introduction of the fuel into the furnace. It was observed that increasing the primary to secondary air supply tends to decrease the temperature at the grate area, core of the furnace, steam collection header and superheater region respectively; the temperatures were found to be between 289 °C and 750 °C. The primary to secondary air setting in Test 2 (40:60) showed increase in temperature at all points inside the furnace (between 482 °C and 785 °C). The flue gases mixed very well more than other three cases Test 1 (30:70); Test 3 (50:50); and Test 4 (60:40). Stable phase was observed at \( h_a = 0.3 \text{ m} \). This suggested that combustion occurred steadily (Razuan, 2011). The freeboard temperature at \( h_s=1.3 \text{ m} \) and \( h_e=1.38 \text{ m} \) was lower about (482 °C).

This was due to the effect of heat losses through the furnace wall. The temperature above the grate decreased as primary air supplied increased, thus an improperly distributed air supplied can reduce the performance of the combustion process. Oxygen decreases gradually along the furnace height in all the test runs. Primary to secondary air setting of (60:40) recorded maximum volume of oxygen (12 %) at the grate area while it was minimal (6.2%) when the ratio of primary to secondary was (40:60). The Plate (1 and 2) shows flame propagation from centerline when firing PKS additive mixture at air supply ratio 40:60 and 30:70 respectively. The yellowish flame color in Plate 2 indicates incomplete combustion probably caused by improper distribution of air within the furnace chamber. Properly distributed air supply improves mixing and enhances combustion process and therefore lowers the pollutant from incomplete combustion.

3.2 Flue gas compositions

Table 3 depicts the gas emissions for different ratio of primary to secondary air supplied. The emissions represent the result of chemical reactions that occurred in the furnace. It was observed that the primary to secondary air setting in Test 4 (60:40) recorded maximum level of CO (550 ppm) (Table 2). This may probably due to poor mixing at the grate area and freeboard region. It was found that decreasing the primary to secondary air setting particularly in Test 2 (40:60) reduces level of CO from 550 ppm to 285 ppm and this tends to lower pollutant from incomplete combustion. Such observations seem to suggest that pollutant emission due to incomplete combustion from grate fired boiler can be effectively controlled by an optimized combustion process. In the same way, Yin et al., (2008) reported optimization of air in grate fired boiler can significantly enhance the mixing and improve combustion process. The highest level of CO\(_2\) in all test cases was low at the
Figure 1: Schematic diagram of PKS combusting furnace for 5 kW power rating

Plate 1: Flame propagation from Center line of the fuel at ratio of pry: sec 40:60
Plate 2: Flame propagation at ratio of pri : sec 30:70
Table 1: Summary of test parameters on effect of primary to secondary air supplied on combustion efficiency and gaseous emission

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Primary: Secondary Air ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30:70</td>
</tr>
<tr>
<td>Fuel feed rate (kg/hr)</td>
<td>17.3</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>760</td>
</tr>
<tr>
<td>CO (ppm)</td>
<td>301</td>
</tr>
<tr>
<td>CO₂ (ppm)</td>
<td>7484</td>
</tr>
<tr>
<td>$L_{\text{thermal}}$ (%)</td>
<td>11.00</td>
</tr>
<tr>
<td>$L_{\text{chemical}}$ (%)</td>
<td>27.76</td>
</tr>
<tr>
<td>Combustion</td>
<td>61.24</td>
</tr>
</tbody>
</table>

Table 2: Parameters and combustion properties at different ratio of primary to secondary air supply

<table>
<thead>
<tr>
<th>Test</th>
<th>Air Rate Flow rate</th>
<th>Temperature (°C)</th>
<th>Bottom Ash collected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Primary (m³/s)</td>
<td>Secondary (m³/s)</td>
<td>Above grate</td>
</tr>
<tr>
<td>Test 1. (30:70)</td>
<td>4.92 × 10⁻⁴</td>
<td>11.48 × 10⁻⁴</td>
<td>760 (± 11)</td>
</tr>
<tr>
<td>Test 2. (40:60)</td>
<td>6.56 × 10⁻⁴</td>
<td>9.84 × 10⁻⁴</td>
<td>785 (± 08)</td>
</tr>
<tr>
<td>Test 3. (50:50)</td>
<td>8.2 × 10⁻⁴</td>
<td>8.2 × 10⁻⁴</td>
<td>673 (± 13)</td>
</tr>
<tr>
<td>Test 4. (60:40)</td>
<td>9.84 × 10⁻⁴</td>
<td>6.56 × 10⁻⁴</td>
<td>620 (± 11)</td>
</tr>
</tbody>
</table>
### Table 3: Gaseous Emission at different ratio of Primary to Secondary air supply

<table>
<thead>
<tr>
<th></th>
<th>Above grate</th>
<th>Core of furnace</th>
<th>Steam collection header</th>
<th>Superheater region</th>
<th>Exhaust port</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO</td>
<td>CO₂</td>
<td>O₂</td>
<td>CO</td>
<td>CO₂</td>
</tr>
<tr>
<td>Test 1</td>
<td>386</td>
<td>3596</td>
<td>10.2</td>
<td>380</td>
<td>4816</td>
</tr>
<tr>
<td>Test 2</td>
<td>450</td>
<td>3608</td>
<td>9.0</td>
<td>356</td>
<td>4944</td>
</tr>
<tr>
<td>Test 3</td>
<td>450</td>
<td>3214</td>
<td>9.0</td>
<td>419</td>
<td>4153</td>
</tr>
<tr>
<td>Test 4</td>
<td>550</td>
<td>3016</td>
<td>12</td>
<td>486</td>
<td>4031</td>
</tr>
</tbody>
</table>

Note: CO and CO₂ were measured in ppm, O₂ (%) of the flue gas

beginning but gradually increases when the palm shell began to burn more efficiently. The maximum level of CO₂ (8446 ppm) accompanied by low level of CO (285 ppm) at h₂=1.38 m above the grate where the freeboard temperature region increases steadily over time. One of the major gaseous emissions which is the main focus according to Nigerian emission limit (www.lng.com) can be ensured at level below the national emission limits (195-856 ppm) for CO and at 6% O₂. This is evident in Table 2 where CO and O₂ decreased within primary to secondary air ratio of Test 2 (40:60)

#### 3.3 Bottom Ash Collected

The bottom ashes residue was collected after each combustion test as shown in Table 2. Less than 18 % of the initial material was trapped as bottom ash and unburned carbon. The most abundant elements found in ash sample were Al, Ca, Fe, K, Mg, and S

#### 3.4 Combustion Efficiency

The maximum combustion efficiency (64.5 %) was observed at the primary to secondary air ratio (40:60) (Table 1). This air setting has highest CO₂ concentration, temperature and lowest value of CO in the flue gas. Further increase in primary to secondary air ratio such as (30:70); (50:50); (60:40) decreases in residence time of particles which lead to increase in unburned carbon and decreases combustion efficiency. The maximum combustion efficiency (64.5 %) obtained in this study is well comparable with other efficiencies of biomass combustor for Agro-industry according to Izah et al., 2016.

#### 4.0 CONCLUSIONS

This study was focused to evaluate effects of the ratio of the primary to secondary air supply on combustion and emission performance. Combustion efficiency was calculated and the results indicated that the primary to secondary air supply of 40:60 recorded highest combustion efficiency (64.5 %) and minimum gaseous emission can be ensured at a level below the national limits (195-856ppm) for CO and at 6% O₂. Therefore, palm kernel shell additive mixture can serve as a source of fuel to supply energy needed in the palm oil mill conveniently, which can favorably be compared with other source of energy such as fuel oil and LP gas fuel. However, it would be most
attractive to find additives to be mixed with PKS from wastes materials with low costs and large amounts available than the use of calcium oxide (CaO) and aluminum oxide (Al₂O₃).

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