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Performance evaluation of combustion of palm kernel shell and coconut husk blend in a pilot-scale grate furnace

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ABSTRACT

Pollution resulting from the use of stereotypical fuels for energy generation has been a great menace to the air we breathe. Co-combustion of biomass fuels has proved effective against the deficiencies associated with the burning of individual biomass on its own. This study aimed at investigating the combustion of Palm Kernel Shell (PKS) and Coconut Husk (CH) blend in a grate furnace. The proximate and ultimate analyses of the mix of PKS and CH were determined using ASTM 3174-76 method. Four combustion tests were carried out with a 2 kW grate furnace, where the effects of temperature distribution, flue gas emissions (CO_2, CO, and NO_2), and combustion efficiency were measured. All the experimental tests were performed using varying primary-secondary air ratio of (40:60). The temperature distribution at different positions (H1, H2, H3, H4, and H5) in the combustion unit using PKS and CH blend (PKS-CH) ratio of 100:00, 70:30, 60:40, and 50:50 was measured. Temperature data were recorded for 50 minutes after a stable bed temperature of 248.7 °C was reached. The results indicated that the highest temperature immediately above the grate (H1) was 720.9 °C for 60:40 fuel proportions. A more significant temperature difference of 356.4 °C between the bed temperature and H1 temperature was recorded for 70:30 fuel proportions. The average deviation from temperatures at H1 to H5 at 50 minutes of the experiment was approximately 122 °C. For each co-combustion fuel option, combustion efficiency increases with time following the same pattern as CO_2 emission. The combustion efficiency was maximum (62.11%) at 70:30 PKS-CH ratios, which conversely showed a low CO emission of 302 ppm.

Keywords: co-combustion; coconut husk; grate furnace; palm kernel shell; temperature distribution.

INTRODUCTION

Residues obtained from processing agricultural products hold constituents whose values are much less than the total cost of processing for man's benefit (Obi *et al*., 2016). These agricultural wastes can be classified as biomass. The environmental problem resulting from the use of fossil fuel and its limited availability has instigated the demand for green energy (Basheer and Ali, 2019) and productive use of biomass as an alternative for generating energy. Moreover, the rise in climate change relative to the emission of CO_2 and other greenhouse gases from fossil fuel consumption is now of global concern (Yin *et al*., 2008; Skreiberg *et al*., 2012). In mitigating these effects, however, the locked up energy bounded in biomass can be released by combustion or burning (Yin *et al*., 2008; Oladosu *et al*., 2019). Among

the standard technologies for extraction of energy from biomass is grate furnace combustion, whose efficiency, based on the type of fuel and mixing quality of flue gas and combustion air, has been notable on large scale designs. Yin *et al*. (2008) described the significance of grate assembly in a gas-fuel mixture. However, a less significant efficiency has been recorded for small scale application (Gaegauf and Salerno, 1991; Bühler, 1992; Sjaak and Jaap, 2006). Thus, low moisture content, varying particle sizes, and low ash content are considered the qualities of biomass fuels apt for grate furnaces (Thomas *et al*., 2019). Nussbaumer (2003) stated, on the other hand, that biomass with moisture content up to 60% could be directly burned as well. The process of combustion in a grate furnace is divided into a number of steps basically feeding of the fuel unto the grate and starting up the fire (Kuijk, 2008). Najmi and Rosli (2006) reported inadequate air-fuel mixing and fuel distribution in their investigation of the combustion characteristics of palm kernel shells in an inclined grate furnace.

Palm Kernel Shells (PKS) are carbonaceous shell fractions left after processing and crushing of palm fruit. Thermal conversion processes may convert this high carbon content as a source of heat energy (Najmi *et al*., 2006; Edmund *et al*., 2014; Husan *et al*., 2002; Torres-Fuchslocher and Varas-Concha, 2015; Oladosu *et al*., 2019). Table 1 shows the ultimate and proximate analysis of raw residues PKS carried out by Onochie *et al*. (2017). In the developing countries of the world, PKS is either combusted to provide the needed energy at palm oil mills or cumulated to form composts. Ordinarily, oil mills use PKS, despite its smoke emission deficiency, as fuel in boilers to produce heat and electricity. Burning PKS separately with its high nitrogen content results in significant NO emission. Because of this fact, one of the widely used countermeasures is to ameliorate the calorific value of the PKS by co-burning with woody biomass such as sawdust (Edmund *et al*., 2014). In the same vein, Suheri and Kuprianove (2015) took on the position that co-combustion appears as an efficient means of improving the operational problems linked with burning PKS solely. The report in previous studies on the co-combustion of biomass showed that adverse environmental impacts accompanied by burning individual fuels with low calorific value or intolerable emissions could be managed effectively by using such fuels together. Of such fuels that can be co-fired with PKS is coconut husk. Raman *et al*. (2011) characterized coconut husk, and the results are presented in Table 2.

Past studies on the biomass combustion suggested that air staging and fuel staging strategies can be employed to optimize the combustion performance of biomass in a fluidized bed and grate combustors (Khodaei *et al*., 2017; Salzmann and Nussbaumer, 2001; Ninduangdee and Kuprianov 2014; Yin and Li 2017), but the startup and running cost of operations associated with these techniques make it difficult to be operated by small scale business. Therefore, it becomes imperative to work further to enhance the combustion process in small scale grate furnace technology. This paperwork aims to investigate the combustion of a selected fuel blend, PKS-CH, with a varying proportionate mixture of the two fuels in a pilot-scale grate furnace. The work focuses on temperature and emissions at different heights in the furnace against time. In the following sections, an explanation of the experimental setup and results are presented, after which conclusions are drawn.

Table 1. Proximate and ultimate analysis of palm kernel shell (Onochie et al., 2017).

Proximate Analysis						
Element	Carbon	Oxygen	Hydrogen	Nitrogen	Sulfur	Calorific value
Weight (%)	47.88	42.69	5.15	0.94	0.10	16.9MJ/kg
Ultimate Analysis						
Property	Moisture	Ash	Fixed Carbon	Volatile matter		
Weight (%)	10.23	3.24	1.42	85.11		

Table 2. Ultimate and analysis of oven dried coconut husk (Raman et al., 2011).

Proximate Analysis						
Element	Carbon	Oxygen	Hydrogen	Nitrogen	Sulfur	Calorific value
Weight (%)	47.88	42.69	5.15	0.94	0.10	16.9MJ/kg
			Ultimate Analysis			
Property	Ash	Fixed Carbon	Volatile matter			
Weight (%)	2.6	6.7	90.7			

MATERIALS AND METHOD

PKS-CH characterization

In this study, African PKS and CH originated from Ogbomoso Southwestern, Nigeria, were employed as fuels. These fuels were dried in air for 3 to 4 days to remove moisture. Excessive moisture levels would significantly decrease combustion rates and lower energy recovery (Ahmad *et al*., 2008). The shells were crushed and further reduced to smaller grains using granulator (SG-16 Series) and blender accordingly. The grains were subsequently sieved to 6 mm. The proximate and ultimate analyses of the samples (PKS-CH) were determined using the ASTM 3174-76 method. The result of these analyses is represented in Table 3. PKS-CH showed a very high volatile content (72.93 wt. %), with a small amount of fixed carbon (16.76 wt. %). The net calorific value (LHV) of the PKS-CH quantified around 18.67 MJ/kg was established to correspond to that of PKS additives mixture (18.80 MJ/kg) by Kareem *et al*. (2018). Low sulphur content in PKS-CH mix also indicates less likelihood of SOx emission, consequently eliminating the need for postcombustion reduction of the emission.

Table 3. Ultimate and proximate analysis of PKS-CH blend.

Fuel	**PKS-CH blend**
Proximate Analysis (%)	
Moisture	8.64
Ash	1.34
Fixed Carbon	16.76
Volatile Matter	72.93
Ultimate Analysis (%)	
Carbon	51.46
Oxygen	42.67
Hydrogen	5.12
Nitrogen	0.48
Sulphur	0.03
Calorific value (MJ/Kg)	18.67

Experimental setup and procedure

The furnace was designed to have a rectangular shape with a height of 1.2 m supported on a four-legged stand of 0.45m height. The furnace has 5 mm thick metal wall made of mild-steel (Basheer, 2020) lined internally with refractory brick insulations with an internal area of 0.5974 m^2. A schematic representation of the furnace is shown in Figure 1.

The combustion chamber is approximately 0.4037 m^3 in volume. Apart from the furnace body, the experimental setup included a manual fuel feeder, 2HP- air compressor that forces air through the primary and secondary air pipes with gate valve regulating air intake as shown in the exploded view of PKS-CH combusting furnace in Figure 2. Also, facilities for measurement such as 12 points channel temperature recorder, gas analyzer, and airflow meters were used. To ensure quality air-fuel mixture required for good combustion, a split air supply system was employed (that is, primary and secondary airflow from below and above the grate, respectively).

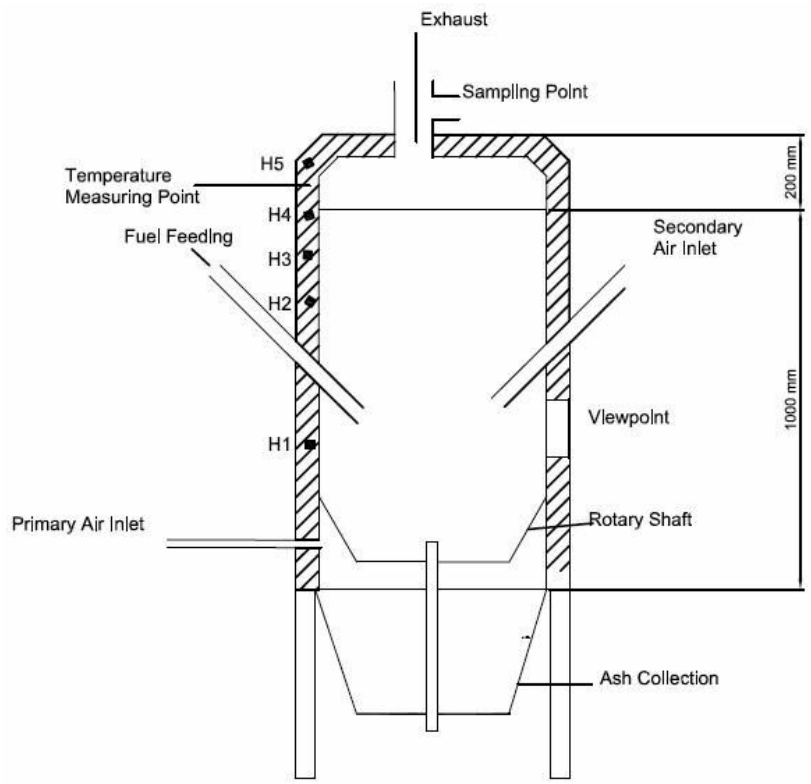


Figure 1. Schematic diagram of the combusting furnace.

All the experimental tests were performed using a staged air ratio of 40:60 (primary to secondary) of the total air supply following the optimum value also reported by Kareem *et al*. (2018). Combustion chamber temperatures were taken at 5 different positions above the grate using sheathed Type K thermocouples of 1.5 mm diameter and 80 cm long. The thermocouples were located at 100, 250, 400, 550, and 700 mm above the grate. These positions were labelled H1, H2, H3, H4, and H5, respectively, and the temperatures were displayed on 12 channel temperature recorder. The flue gas produced from the combustion process was evaluated using a ToxiRAE Pro gas analyzer and Aeroqual series 500 portable air quality monitor (Richard Gassman, 2015). The gas analyzer probe was positioned at the chimney to obtain the concentration of different flue gases that were produced, CO, CO_2, and NO_2 typically. The performance of the furnace was found using a simplified formula of combustion efficiency (η), as suggested by Nussbaumer and Good (1998).

$$\eta = 100 - V_{therm} - V_{chem}\,(\%) \quad (1)$$

where V_{therm} - thermal losses of the flue gas [%]

V_{chem} chemical losses of the flue gas [%]

$$V_{therm} = f\frac{T_a - T_u}{CO_2} \quad (2)$$

where T_a is the temperature of the flue gas [°C], T_u is the ambient temperature [°C], CO_2 is the value read by an infrared sensor [vol.-%], and f is the fuel-specific factor [%/°C].

$$V_{chem} = \frac{CO\ 11800}{CO_2 + CO\frac{h_{u\ atro}}{100} - 0.25u} \quad (3)$$

where $h_{u\ atro}$ is the heating value of fuel and CO is carbon monoxide [vol.-%],

and CO_2 is carbon dioxide [vol.-%]

$$f = \frac{20.9 - \%O_2}{\%CO_2} \quad (4)$$

Low and high efficiency of the combustion process are indicated by the degree of temperature in stack and gas.

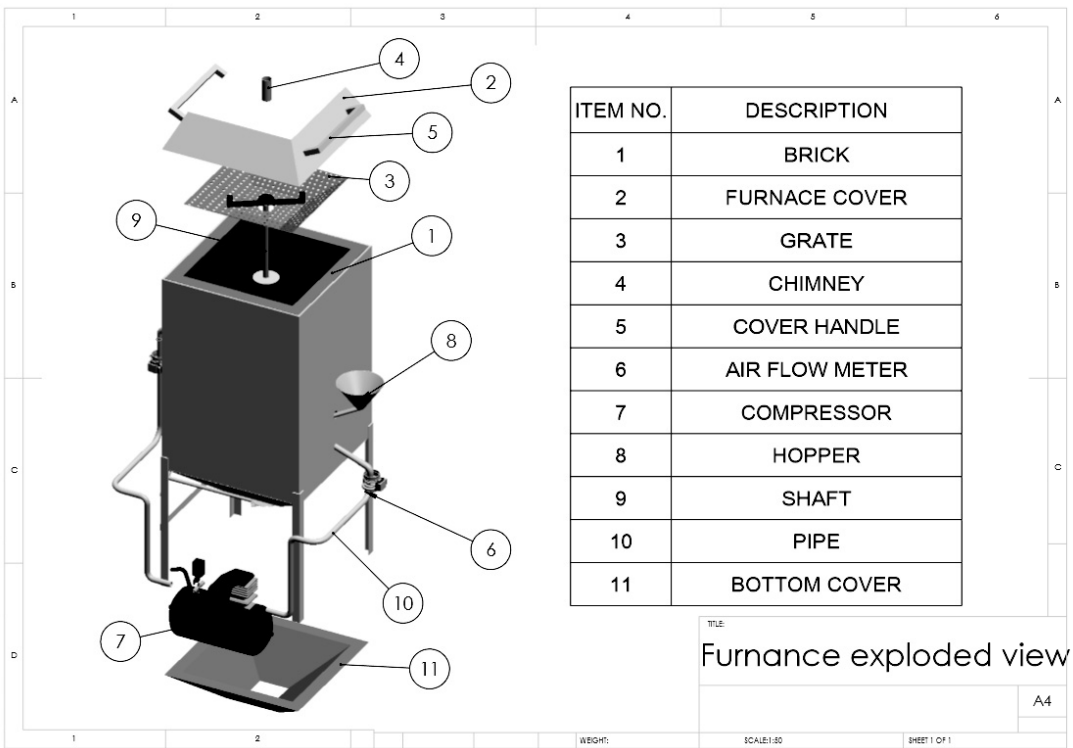


Figure 2. Exploded view of PKS-CH combusting furnace.

RESULTS AND DISCUSSION

Temperature distribution

Table 4 summarizes test parameters and combustion properties at different PKS-CH proportions and heights. Temperature data was recorded for an experiment time of about 50 minutes after a stable bed temperature of 248.7 °C was reached. Figure 3 (a)-(d) shows the temperature profiles measured at different height H1-H5 for PKS-CH mix: (a) 100:00, (b) 70:30, (c) 60:40, and (d) 50:50. For 100:00 fuel ratio, the maximum temperature recorded was 472 °C at H1 immediately above the grate and 339 °C at the exhaust port, as shown in Fig. 3(a). A higher temperature of 667 °C was recorded at H1 for 70:30 fuel mixture and 593 °C at the exhaust port. However, the highest temperature immediately above the grate (H1) was recorded to be 720 °C for 60:40 fuel mix. The relatively high temperature was because of the percentage of coconut husk in the fuel mixture. Even so, the highest temperature difference between the bed temperature and temperature at H1 was recorded to be 356 °C for 70:30 fuel proportion, which indicates a significant combustion temperature compared with other test cases. Coconut husk burned faster than PKS, and this helps PKS burn very well too. The low temperature above the grate for 100% PKS combustion can be attributed to the slower combustion kinetics due to slight hindrance in igniting PKS (Najmi et al., 2006), although burning of PKS during the experiment was not as difficult due to local pyrolysis of PKS done beforehand. In the tests, coconut husk catered for the deficiency of PKS in terms of preignition problem and pollution concerns.

The average difference between the temperatures at H1 and H5 at 50 minutes of the experiment was approximately 122 °C. This difference shows that high gas cooling rates occurred as the combustion gases flow from the primary combustion area to the exhaust, which is only at about 83 cm distance vertically. The likely cause of this would be the deficient makeup of refractory bricks used for wall insulation, as well as a draught from excess combustion air towards the exit of the furnace. Appendix A (I) shows the detailed temperature distribution at different times and positions (H1, H2, H3, H4, and H5) in the furnace using the PKS-Coconut ratio of 100:00, 70:30, and 60:40.

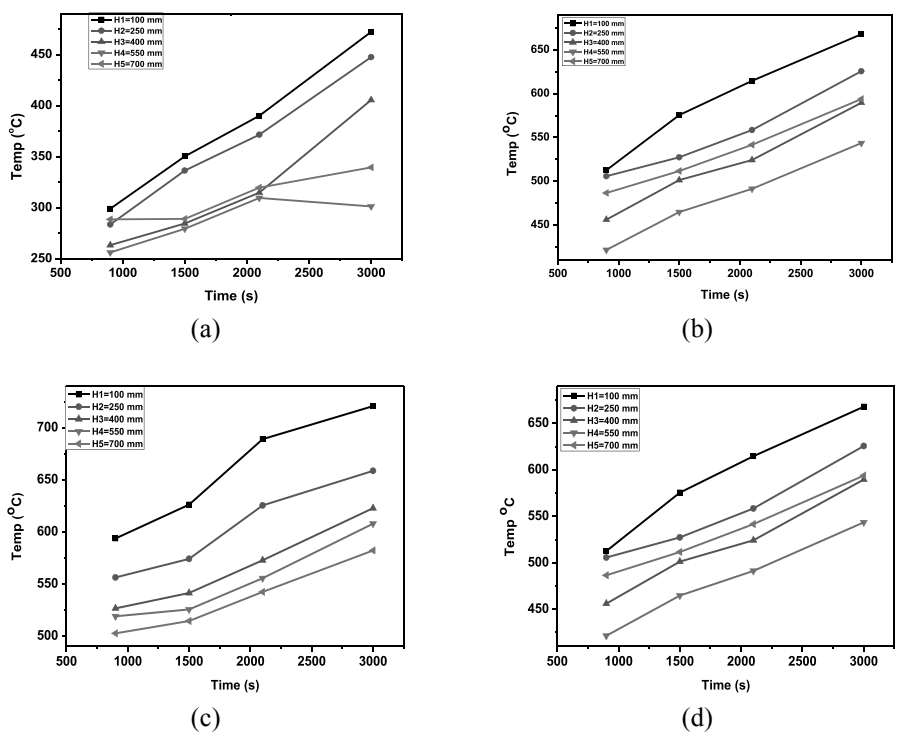


Figure 3. Temperature profile at different heights for co combustion of palm kernel shell and coconut husk proportions of (a) 100:00, (b) 70:30, (c) 60:40, and (d) 50:50.

Table 4. Summary of temperature distribution, gaseous emission, and efficiency for PKS-CH proportions.

Parameter		PKS-CH Fuel Proportions			
		100:00	**70:30**	**60:40**	**50:50**
Bed Temperature (^{o}C)		248	311	402	481
Temperature Distribution (^{o}C)	H1	390 (± 90)	590 (± 80)	660 (± 60)	590 (± 30)
	H2	370 (± 80)	570 (± 60)	610 (± 50)	560 (± 30)
	H3	340 (± 70)	525 (± 65)	575 (± 45)	530 (± 40)
	H4	280 (± 20)	480 (± 60)	565 (± 45)	500 (± 60)
	H5	315 (± 25)	540 (± 50)	540 (± 40)	495 (± 65)
Gaseous Emission (ppm)	CO_2	8402	7900	7783	7429
	CO	321	302	352	319
	NO_2	0.061	0.056	0.076	0.076
Carbon Combustion Efficiency (%)		57.64	62.11	58.68	57.44

Effect of operating conditions on the distribution of CO_2, CO, and NO_2

In this experiment, baseline data was first obtained for a single combustion of 100% of palm kernel shell. Also, co-combustion tests at 70:30 and 60:30 proportions of PKS to coconut husk were performed. Figure 4 (a)-(c) shows the effect of PKS-CH blend on the emission of (a) CO, (b) CO_2, and (c) NO_2. 100 % full PKS combustion shows that the CO_2 concentration in the flue gas is within the range of 8402–7052 ppm, while 70:30 proportion gave CO_2 concentration range within 7475–7783 ppm, 7783– 6462 ppm range for 60:30 proportion, and 7429–6167 ppm range for 50:50 proportion in 50 minutes of combustion. It was observed that CO_2 concentration in the flue gas increases with time in the 4 experiments. It was also evident that CO emission was detected for the entire combustion process. The maximum level of CO is at 449 ppm, and the minimum is at 302 ppm for 100:00 and 70:30 fuel proportions, respectively. However, CO concentration in the fuel gas decreases with time. The operating conditions and flue gas analysis results are presented in appendix (II).

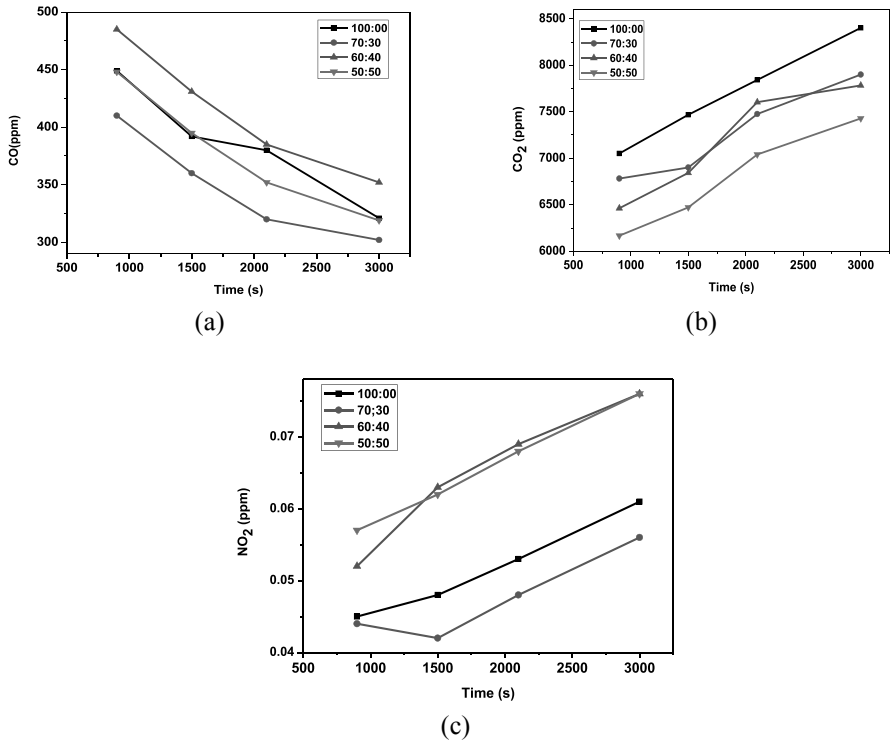


Figure 4. Effect of PKS-CH blend combustion on emissions of (a) CO, (b) CO_2, and (c) NO_2.

Carbon combustion efficiency

Carbon combustion efficiency was tested for the four fuel blend proportions at different times, as shown in Figure 5. Appendix (II) shows the carbon combustion efficiency of fuel with time, along with the relevant parameters required for their prediction. For each co-combustion fuel option, combustion efficiency increases with time following the same pattern as CO_2 emission. As seen in Figure 5, the combustion efficiency was characterized by its maximum of 62.11% at PKS:CH = 70:30, which, however, showed a low CO emission. Thus, based on CO emission and ease of attaining stable combustion, a fuel blend of 70:30 PKS-CH will give better combustion in time.

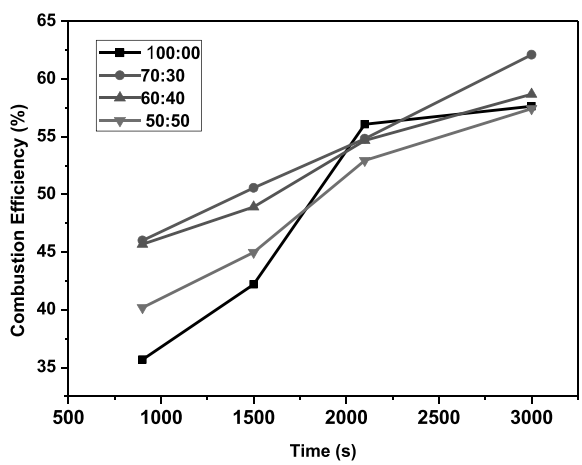


Figure 5. Combustion efficiency for PKS-CH proportions at different times.

CONCLUSIONS

Combustion of palm kernel shell and coconut husk has been performed in a rectangular grate furnace designed as an improvement on the cylindrical grate combustor such that turbulent mixture of the fuels is achieved through a rotary mechanism. The results of a carbon combustion efficiency of 62.11 % recorded at 70:30 fuel blend show that PKS could be burnt efficiently with coconut husk and that the blend proportions of these fuels have a significant effect on temperature and emission characteristics. It was found that local pyrolysis of PKS before burning aided significantly in the combustion process; however, it can be inferred that the secondary fuel (coconut husk) burns at a faster rate, which assisted in starting up the burning of PKS.

The result further indicates that palm kernel shell and coconut husk may be co-fired in a grate furnace to generate significant energy for steam power plant, while the problems associated with burning PKS alone are mediated. With a further investigation into the particle sizes of the fuel blend and an increase in excess air supply, the unburnt carbon may be significantly reduced and the combustion efficiency improved.

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Appendix A

I. Temperature distribution at different positions in the furnace for different fuel proportions.

Fuel mixture	Time (s)	Temperature (°C)				
		H1	**H2**	**H3**	**H4**	**H5**
		Bed Temperature = 248.7 °C				
100:00	900	299.0	283.6	263.3	256.2	288.6
	1500	350.3	336.4	284.6	279.3	289
	2100	390.0	371.5	314.8	309.6	319.7
	3000	472.2	447.5	405.4	301.3	339.5
		Bed Temperature = 311.4 °C				
70:30	900	512.6	505.6	456.1	421.4	486.5
	1500	575.5	527.3	501.3	464.7	511.6
	2100	614.7	558.4	524.2	491.3	541.5
	3000	667.8	625.6	589.6	543.5	593.8
		Bed Temperature = 402.5 °C				
60:40	900	593.7	556.3	526.5	518.9	502.6
	1500	626.2	574.1	541.4	525.6	514.5
	2100	689.1	625.4	572.8	555.6	542.3
	3000	720.9	658.6	622.8	607.9	582.1
		Bed Temperature = 481.32 °C				
50:50	900	622.9	589.5	569.2	562.1	574.52
	1500	649.1	632.2	583.4	578.1	587.2
	2100	600.7	582.2	545.5	540.3	550.6
	3000	555.3	530.3	488.2	444.1	422.3

II. Effect of fuel blend proportion on gaseous emission and combustion efficiency.

Fuel Proportion (PKS:CH)	Time (s)	Parameters			
		CO (ppm)	CO_2 (ppm)	NO_2 (ppm)	Carbon Combustion Efficiency (%)
100:00	900	449	7052	0.045	35.68
	1500	392	7468	0.048	42.2
	2100	380	7842	0.053	56.08
	3000	321	8402	0.061	57.64
70:30	900	410	6782	0.044	46.01
	1500	360	6900	0.042	50.57
	2100	320	7475	0.048	54.82
	3000	302	7900	0.056	62.11
60:40	900	485	6462	0.052	45.67
	1500	431	6843	0.063	48.92
	2100	385	7603	0.069	54.68
	3000	352	7783	0.076	58.68
50:50	900	448	6167	0.057	40.19
	1500	395	6472	0.062	44.97
	2100	352	7041	0.068	52.95
	3000	319	7429	0.076	57.44