

Performance evaluation of a small scale palm fruit biomass fired boiler

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Abstract: This study evaluated the performance of a boiler designed for small scale palm fruit processing. The boiler was evaluated for its fuel consumption, steam production rate and efficiency using 100 kg of different fuel samples (shell, palm fibre, empty fruit bunch (EFB) and wood) with known calorific value and their combinations for a period of 60 min firing time. The rate of fuel consumption by the furnace differs with the type of fuel materials as 100 kg of shell and 100 kg of wood burnt within 55 min firing time while the combination of shell and wood was burnt within 60 min of its firing time under the same condition. Combination of shell and EFB lasted for 50 min during firing while EFB alone burnt completely within 35 min. The highest quantity of steam (17.99 kg/min) and maximum boiler efficiency (79.6%) were recorded when fired with EFB only while 10.96 kg/min steam production rate and 76.4% efficiency were recorded when fired with shell and EFB combination. Combination of shell and wood produced 10.31 kg/min of steam and 76.6% boiler efficiency while 11.31 kg/min of steam and 76.9 % boiler efficiency was obtained with wood only. Combination of shell, EFB and fibre gave 15.28 kg/min of steam and 73.1 % boiler efficiency while 10.32 kg/min of steam and 76% boiler efficiency was obtained with shell only. The study concluded that the boiler developed using adequately-prepared locally-available materials has the potential to be incorporated into the small scale palm fruit processing technology profile and has the capacity to supply the steam requirement in the plant, thereby bridging the identified gap in the small scale palm oil process line.

Keywords: fire-in-tube, water-in-tube, inlet air preheat chamber, fuel material, firing time, efficiency.

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1 Introduction

Palm oil is a very important product in palm fruit processing. It has extensive domestic and industrial applications. As a result, there is an increasing demand for palm oil in Nigeria; the bulk of palm oil being produced from the small and medium scale processors. These processors lack appropriate technology for processing palm fruit into palm oil. The extraction efficiency of the technology currently used is low. One of the gaps in the process line is a heating mechanism (a boiler) as used in large scale plants. Such mechanism that will utilise the wastes from palm fruit processing will go a long way in improving the lot of the processors.

Ineffective utilization of biomass from the oil mill, constitutes environmental hazard and pollution, it also

leads to emission of strong irritating smell due to microbial breakdown activities at dump sites. This calls for an efficient utilisation of this biomass as fuel for the industry (Salako et al., 2011). In a standard palm oil mill, 20 - 24 t of crude palm oil and about 4 t of palm kernel can be obtained from every 100 t of FFB processed, therefore the remaining 72% - 76% of the FFB comes out as waste in various form. These waste product can be in form of EFB, palm fibre and palm kernel shell. These waste products are being referred to as by-products in a large and medium scale mills. This is because the by-products are being ploughed back into the oil milling operation to serve as fuel for the boiler system (FAO, 2002).

The empty bunches contains a large amount of moisture, therefore it has to be partly sun dried before using as fuel. Another economic use for the empty bunches is to return them to the plantation as a mulch to enhance moisture retention and organic matter in the soil. Owolarafe (2007) has however indicated that the economic value of EFB for power generation was 3.5 times that for mulching. The palm

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kernel shell is also used as a source of fuel for the boilers and can be disposed of as gravel for plantation roads maintenance. Blacksmiths also buy the shells to use as fuel material in their casting and forging operations (FAO, 2002). The fibre recovered from the nut/fibre separation stage is a good combustible material and finds ready use as fuel to boil the fruit. It constitutes the bulk of material used to fire the large boilers used to generate superheated steam to drive turbines for electrical power generation in large-scale plants (Husain et al., 2003; FAO, 2002). Boiler ash is recycled as fertilizer and factory floor cleaning agent. The potash in the ashes reacts with the oil to form a weak potash soap that is washed away with water.

Small-scale mills also use the fibre and bunch waste as fuel material. Most small-scale mills do not undertake the shelling of recovered palm nuts. The nuts are sold to palm kernel processors. Wood consumption of small-scale operations is relatively small because of the recycling of the fibre and bunch waste as the main fuel source (Owolarafe, 2007). The medium-scale operators tend to supplement their internally generated solid waste fuel sources with wood for firing their boilers. The impact on the local tree population is significant enough to cause factories to close while foraging for wood supplies (Owolarafe, 2007). Empty fruit bunches are underutilised in most processing centres with the bulk of it wasted and allowed to decay in the piles (Owolarafe, 2007).

According to Chow et al. (2008), the empty fruit bunches are the most bulky and difficult palm fruit biomass to handle compared to the fibre and shell. The fibre and shell also have the advantage of being in comminute form and are thus, easily combusted in the mill. The shell has a higher calorific value and better physical form and combustion properties, and is most highly sought after as alternative fuel. The empty bunches not only contain a high content of water but are bulky and need much pre-treatment before they can be burnt.

Agricultural residues have a good energy potential that can compare favourably with other fuel materials. This is due to their high calorific energy potentials. Calorific energy content of a particular fuel material is a function of its moisture content. Therefore Chow et al. (2008) stated that palm fruit biomass if properly dried can generate energy close to the energy being generated from coal.

2 Methodology

The design of the boiler was based on shell and tube

heat-exchanger and consists of various component parts like; the furnace, blower, suction pump, boiler drum, water tubes and the fire tubes as shown in Figure 1 below. The water tube is embedded in the furnace such that heat generated from the fuel combustion can be recovered through heat exchanging principle. The flue gas from the furnace is channelled into the fire-in-tube arrangement in the boiler drum for further heat recovery. The flue gas from the boiler drum is channelled through the air-inlet preheat-chamber for final heat recovery stage. Therefore heat is being recovered in three different stages to ensure high efficiency of the boiler. The roof and the door of the furnace were lagged with fiber glass to retain heat in the furnace thereby reducing heat loss through the roof and the door. The dimensions of the boiler used for this study are as Table 1.

Table 1 The dimensions of the boiler

Parameters	Value
Furnace dimension /(m×m×m)	1.2 × 0.75 × 1.8
Water tube area/(m×m)	1.0 × 0.5
Fire tube length/m	0.6 (× 3 parallel gangs)
Length (boiler drum)/mm	1200
Diameter (boiler drum)/mm	1100

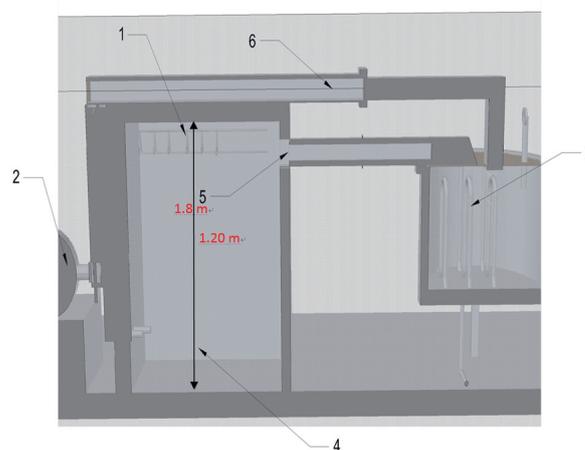


Figure 1 Biomass fired boiler (sectional view)

1. water-in-tube
2. blower
3. fire-in-tube
4. furnace
5. flue gas
6. flue gas out

The temperature of the feed water into the water tube in the furnace was 36°C and rose to 95.2°C before getting into the boiler drum where the final temperature of the water was measured. The boiler was evaluated for its rate of fuel consumption, rate of steam production and its efficiency using six different fuel samples.

The rate of fuel consumption of the boiler was

determined based on the time it takes the fuel to reach complete combustion. The boiler was fired with 100 kg of fuel sample of a known calorific value and the effect of the fuel sample on the steam properties was monitored at 5 min. The point at which the steam temperature and the vapour pressure started dropping indicated the point of complete combustion of the fuel sample, therefore the rate of fuel consumption was measured in kg per firing time (kg / min).

The properties of the steam produced namely: temperature, pressure, enthalpy etc., were monitored based on the type of fuel combination used in firing the boiler. The experiment was a closed system; therefore the rate of steam production was calculated from the properties of the steam produced when fired with different fuel samples using the equation below as stated by Geankoplis (2003).

$$Q = M_s H_g + M_s C_p \Delta T \quad (1)$$

$$C_p = 4.2 \times 10^3 \text{ J/kg K}$$

where, Q was heat flow into the feed water, kJ/min. M_s was quantity of steam generated, kg/min. H_g was enthalpy of saturated steam at maximum temperature, kJ/kg.

C_p was specific heat capacity of water. ΔT was change in temperature.

Therefore, the quantity of steam produced was evaluated using the formula:

$$M_s = \frac{Q}{H_g + C_p \Delta T} \quad (2)$$

The quantity of heat energy (Q) supplied by the fuel samples was calculated using the product of the calorific energy content of the fuel sample (kJ/kg) and the quantity of the fuel sample per firing time (kg/min). The change in

temperature is the different between the inlet temperature (95.2°C) and final temperature of the feed water in the boiler drum. Also the enthalpy (H_g) of the steam in kJ/kg was gotten from the steam table.

The boiler efficiency was also evaluated based on the ratio of energy in steam generated to the energy supplied by the burning biomass residue per 60 min firing time as stated by Hussain et al., (2003).

i.e.

$$\eta_b = \frac{M_s \times (H_g - H_f)}{q \times C_v} \times 100\% \quad (3)$$

where,

H_f was enthalpy of liquid ,
 q was quantity of fuel used in kg/min,
 C_v was calorific value of biomass.

3 Result and discussion

The result of the evaluation of the boiler is detailed below. The fuel samples behaved differently when used to fire the boiler under the same experimental condition and procedure. These differences give room for comparison between these fuel samples.

3.1 Effect of fuel material on steam temperature

Figure 2 below shows the effect of these different fuel materials on steam temperature per time. It could be observed that the temperature of the steam produced when fired with 100 kg shell increased noticeably between 25-35 min firing time and became almost constant thereafter. Maximum temperature of the steam produced (129°C) was attained at 55 min firing time and later dropped slightly to 128°C at the 60th min.

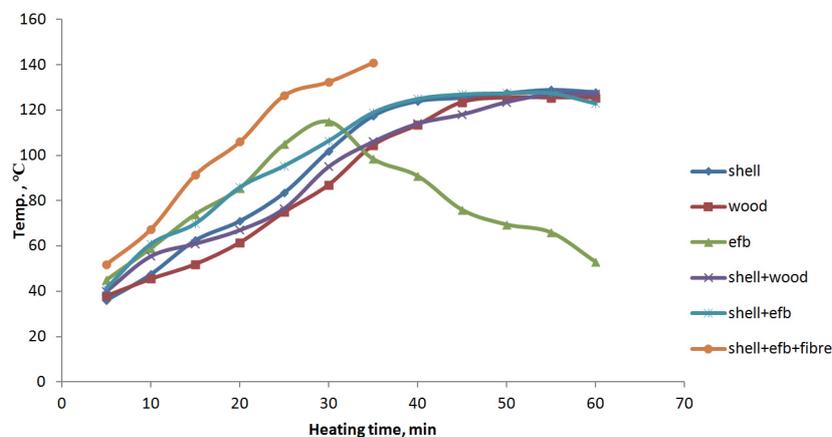


Figure 2 Effect of fuel materials on steam temperature

This result can be attributed to the fact that shell has a higher GCV in compares with other fuel samples, it is in comminute

form, and has a better physical and combustion properties and therefore, burnt for a longer period of time in the furnace.

On the other hand temperature of the steam produced when fired with 100 kg wood, reached the maximum of 125.5°C at 50 min firing time and became constant thereafter up to 60th min of the experiment. The steam temperature increased noticeably between 20 - 45 min firing time as shown. Wood exhibit a similar property when compared with shell as it also burnt for a longer period of time in the furnace.

About 100 kg quantity of the sample of EFB fed into furnace burnt completely within 30 min firing time. The temperature of the steam produced was 115°C at 30 min firing time. Empty fruit bunch is more bulky and requires more of pre-treatment before it can be burnt.

The combination of shell (50 kg) and EFB (50 kg) with average GCV of 15627.5 kJ/kg produced 127.5°C steam temperature at 50th min of the firing time. The temperature and pressure of the steam produced increased gradually from the start of the experiment up to 55 min firing time and dropped thereafter as shown in Figure 2.

The combination of shell (50 kg) and wood (50 kg) with average GCV of 16154.5 kJ/kg produced 127°C steam temperature at 55th min of the firing time. The temperature of the steam produced increased gradually from the start of the experiment up to 55 min firing time and remained constant at 127°C up to 60th min of the experiment.

The combination of shell (40 kg), EFB (40 kg) and fibre (20 kg) with average GCV of 15662 kJ/kg, produced a better result compare to other fuel materials used in terms of the temperature of the steam produced. The temperature increased rapidly to about 141°C within 35 min firing time. The experiment was terminated at this temperature for safety reasons because the vapour pressure at the temperature

was around 3.5 kPa, which is the limit at which the boiler drum was designed to accommodate in order to avoid major disaster. The effect of fuel type on average temperature of steam produced per fuel samples was observed to be significant at $p < 0.05$.

3.2 Effect of fuel material on the vapour pressure

The pressure increased gradually when fired with 100 kg shell, within the first 25 min, this is the period in which pressure builds up in the boiler drum and later increased rapidly between 25 - 40 min firing time. The vapour pressure also attained maximum level of 260.5 kPa at 55 min firing time as shown in Figure 3 below.

The pressure of the steam when fired with 100 kg wood reached the maximum 237.5 kPa at 50 min firing time. It was observed that the vapour pressure builds up slowly in comparison with shell, as it increased gradually within the first 30 min of firing time and noticeably between 30 - 35 min firing time. As shown in Figure 3 below, the vapour pressure was constant at 237.5 kPa between 50 - 55 min firing time and later dropped thereafter.

The pressure of the steam produced when fired with 100 kg EFB reached the maximum of 170 kPa at 30 min firing time after which it started decreasing which signifies the point of complete combustion of the fuel material. The vapour pressure builds up within the first 20 mins of firing time, and increased noticeably between 20 - 25 min of firing time.

The combination of shell and EFB with average GCV of 15627.5 kJ/kg, gave maximum vapour pressure of 252.5 kPa at the 50th min firing time. The pressure of the steam produced increased gradually from the start of the experiment up to 50 min firing time and dropped thereafter.

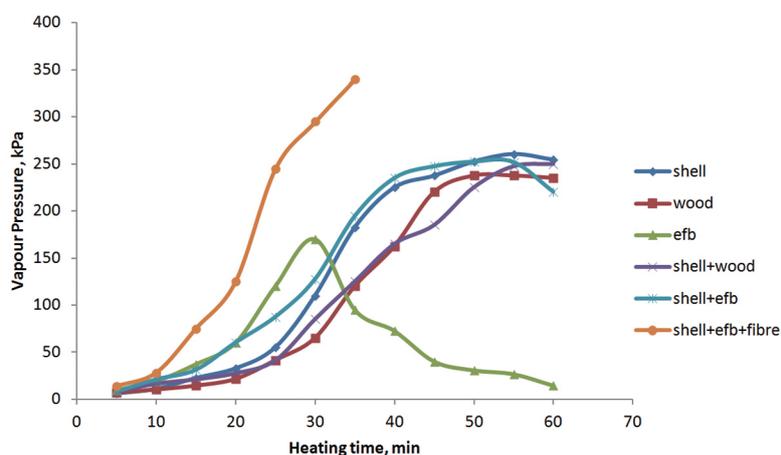


Figure 3 Effect of fuel materials on vapour pressure

The vapour pressure increased throughout the firing time when fired with the combination of shell and wood with average GCV of 16154.5 kJ/kg. The rate of pressure build-up within the first 25 min of the experiment was gradual and was rapid between 30 -55 min of the firing time.

The combination of shell, EFB and fibre with average GCV of 15662 kJ/kg also produced better result compared to other fuel materials in terms of the vapour pressure of the steam produced. The pressure build up in the boiler drum increased rapidly to about 340 kPa within 35 min firing time, at this point the experiment has to be terminated for safety reasons because of the pressure capacity the drum can withstand to avoid failure as stated earlier. The effect of fuel type on average vapour pressure of steam produced per fuel samples was observed to be significant at $p < 0.05$.

3.3 Effect of fuel material on enthalpy

Enthalpy is the amount of energy possessed by a thermodynamic system for transfer between itself and its environment. In a phase change, as from a liquid to a gas, the change in enthalpy of the system is the latent heat of vaporization. The effect of the fuel material on enthalpy

of the saturated vapour is as shown in Figure 4 below. The result is also similar to that of temperature and vapour pressure discussed earlier. Shell produced a maximum enthalpy of 2718.7 kJ/kg at the 55th min firing time while the maximum result of 2714.5 kJ/kg was attained when fired with wood at the 50th min and was constant at that value till the end of the experiment. The enthalpy level reached the peak (2699.2 kJ/kg) at the 30th min firing time when fired with EFB only while the its combination with shell produced a maximum result (2717.2 kJ/kg) at the 50th min firing time. The enthalpy of saturated vapour increased throughout the firing time when fired with the combination shell and wood, as it attained the maximum level (2716.8 kJ/kg) at the 60th min firing time while the combination of shell, EFB and fibre also produced the highest result (2735.4 kJ/kg) in terms of enthalpy (saturated vapour) at the 35th min firing time.

The combination of the palm fruit biomass (shell, EFB and fibre) gave the best result which is also an indication that palm fruit biomass if effectively utilized can supply the energy needed in the palm oil processing industry. The effect of fuel type on average enthalpy (saturated vapour) of steam produced per fuel samples was observed to be significant at $p < 0.05$.

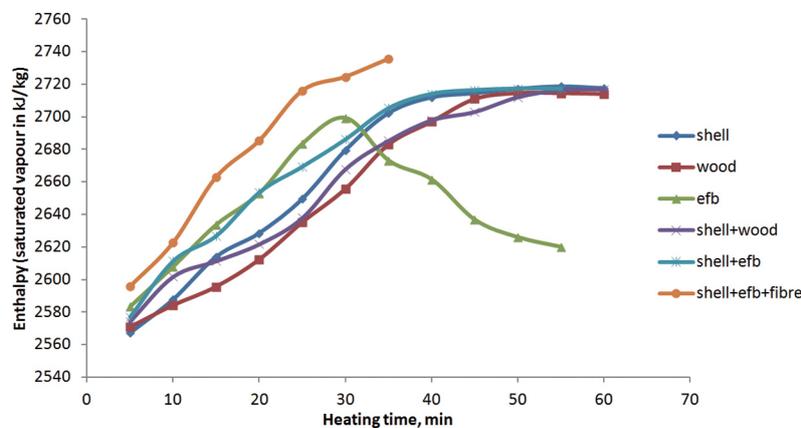


Figure 4 Effect of fuel materials on enthalpy (saturated pressure)

3.4 Effect of fuel material on rate of steam production

The quantity of steam produced (in kg/min) was determined from properties of the steam produced, it was discovered that the highest quantity was obtained when fired with EFB alone and the value was 17.99 kg/min, while the combination of shell, EFB and fibre produced 15.28 kg/min of steam. About 11.31 kg/min of steam was produced when fired with wood alone, while 10.96 kg/min was produced when fired with the combination of shell and EFB as shown in Table 2. Using shell only gave 10.32 kg/min. of steam, while its combination with wood gave 10.31 kg/min. of steam as shown in Figure 5 below.

3.5 Effect of fuel material on efficiency of the boiler

The highest efficiency of the boiler obtained when fired with EFB was 79.6%, while the least efficiency was obtained when fired with the combination of shell, EFB and fibre and it was 73.1%. There was no much difference in the efficiencies obtained when fired with other fuel type as 76.9% and 76.6% were obtained when fired with wood only and combination of shell and wood, respectively. Also combination of shell and EFB gave efficiency of 76.4% while shell only gave an efficiency of 76% as shown in Table 2. Figure 6 shows the effect of fuel material on boiler efficiency.

Table2 Fuel type and Quantity of steam produced / Boiler efficiency

Fuel sample	Quantity of steam produced /(kg min ⁻¹)	Efficiency of the boiler /%
Shell	10.32	76.0
EFB	17.99	79.6
Wood	11.31	76.9
Shell + EFB	10.96	76.4
Shell + Wood	10.31	76.6
Shell + EFB + Fibre	15.28	73.1

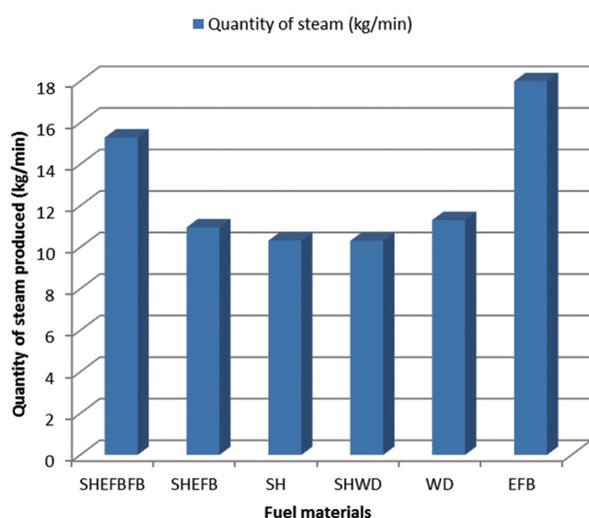


Figure 5 Effect of fuel material on rate of steam production

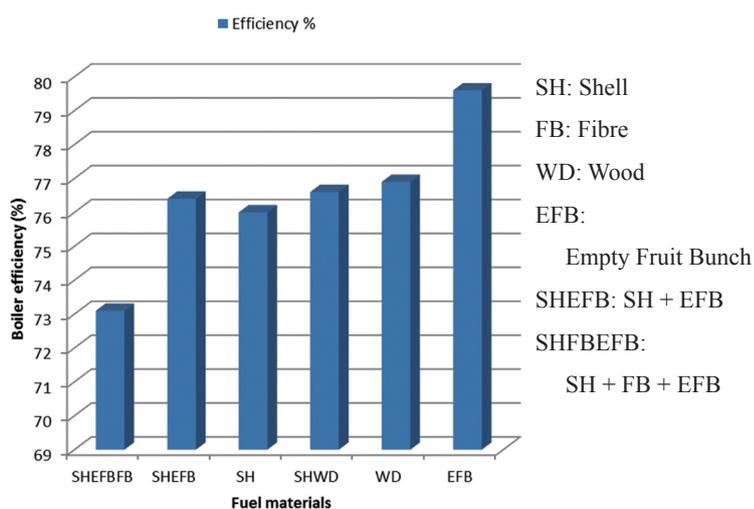


Figure 6 Effect of fuel material on boiler efficiency

4 Conclusion

The study concluded that the boiler developed using adequately-prepared locally-available materials has the potential to be incorporated into the small scale palm fruit processing technology profile and has the capacity to supply the steam requirement in the plant, thereby bridging the identified gap in the small scale palm oil process line

and at the same time there is opportunity for improving its performance. Palm fruit biomass if properly prepared, can serve as fuel to supply the energy needed in the palm oil mill conveniently, which can favourably compare with other source of energy such as coal, and yields a better result compare to wood when used as fuel to fire boiler. Therefore, cleaner environment around the palm oil mills is achievable by ploughing back the waste into the mills as fuel.

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