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Effects of Pine Needle (*Pinus pinaster*) dust on the performance characteristics of sub-bituminous coal briquette for Energy Generation

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ABSTRACT

The effect of pine needle (Pinus pinaster) dust (P) on sub-bituminous coal (C) briquette for energy generation was studied in terms of combustion characteristics, emission profile, and thermal degradation properties. Briquettes of 100% of the pure coal and the biomass were first produced. The ratio for the blending was 1:1 for the binary combination of the biomass with coal. The feed stocks were dried to a moisture content of 5-10% and ground to a particle size of 0.8 mm. Desulphurization, homogeneity and binding were achieved by addition of calcium hydroxide (Ca(OH)2), water and starch, respectively. The briquetting was done using a manual briquetting machine at 5Mpa pressure for 2 h after which they were dried using solar drier for 10 days to obtain low moisture content. Proximate analyses, combustion, emission profile and thermal degradation properties of the coal, biomass and the blend were determined. The combustion and emission analyses showed that the blended briquettes had better combustion characteristics than the single coal briquettes in terms of burning rate (2.96 g/min), time required to boil water (32 min), specific fuel consumption (109.67 g/litre) and thermal efficiency (33%). The concentration of CO and CO2 emitted by the coal briquette was the highest (0.6 ppm and 80 ppm respectively) even though they were within the permissible range stipulated by the World Health Organization Ambient Air Quality Standard (WHO-AAQS) and National Ambient Air Quality Standard (NAAQS) which is 35 ppm for CO and 600 ppm for CO2. Blending the biomass with coal reduced the concentration of the CO (0.6 ppm) and CO2 (33 ppm) evolved during combustion. The particulate matter (PM) emitted by the combination of the biomass with coal was (3051 µg/m3) which is higher than the permissible range in the atmosphere as stipulated by WHO-AAQS and NAAQS stipulated at 150 µg/m3. The blending reduced the concentration of PM evolved when compared to single coal briquette (1475 µg/m3). General results show that combining the pine needle dust with coal briquette improved the combustion, emission characteristic and thermal stability of the briquette.

Keyword: *Coal, briquette, pine needle, combustion characteristics, emission profile.*

INTRODUCTION

Coal is the largest source of energy for the generation of electricity worldwide, as well as one of the largest worldwide anthropogenic sources of carbon dioxide releases. Generally, coal fuel smoke contains a large number of pollutants in the air that are toxic or hazardous to humans [1]. In most Nigerian rural communities, forest resources are the predominant fuel source. The trees are felled, allowed to dry and the different parts of the dried plants are used as fuel wood. Another method of generating heat and light is by converting wood to charcoal. Other plants, apart from trees, are also used as fuel sources. The problem of felling trees for the purpose of using it as fuel source is that it impacts adversely on the environment. One way of limiting the deforestation and protecting the environment is by briquetting of flammable materials.

Briquetting is a process of binding together pulverized carbonaceous matter, often with aid of binder [2]. The common forms of briquettes are the coal briquettes and the biomass briquettes. Biomass briquettes originate from mostly agricultural residues. By converting the agricultural residues to briquettes, a gamut of advantages is derivable. Recently, researchers have shown that blending of coal and biomass will give rise to a briquette with better burning properties and environmentally friendly, and this type is called bio-coal briquette. Bio-coal briquette is a type of solid fuel prepared by compacting pulverized coal, biomass, binder, and sulphur fixation agent [3]. Bio-coal briquettes have more favourable ignition, better thermal efficiency, emits less dust and soot [4]. Several researches on bio-coal briquettes have been carried out using some of these biomass resources and they include: production of bio-coal briquettes using rice straw [5], sawdust [6], olive stone [7] and maize cob [3] etc. *Pinus pinaster* is among the most commercially important tree species valued for their timber and wood pulp throughout the world [8]. Pine needles have tremendous energy. Since the needles are highly photosynthetic, the large amounts of sunlight trapped by these needles are used for energy generation. The by-product of pine needle gasification provides quality charcoal for cooking [9]. Dahel et al. [9] studied pine needle briquette as a promising fuel for gasifier using cow dung as binder. The pine needle briquettes were prepared in different ratios of fuel to binder (40:60, 30:70, 25:75, 20:80). The work showed that 40:60 ratio gave the best results in terms of physical strength and proximate analysis, while the amount of CO was 10% which was adjudged suitable for smooth engine operation if mixed with woody biomass.

Pandey at al. [10] studied the physico-chemical properties of pine needle ash as a biomass briquette using clay as binder. The results showed that pine needle ash is a good source for briquetting having thermal efficiency of 27.01% which was higher than that of fuel wood (15.55%). Again, Musa [11] carried out thermal degradation of *Pinus pinaster* needles using Direct Scanning Calorimetry (DSC). They observed three steps in the thermal degradation of the needle which are dehydration, oxidation of evolved gases and char combustion. Kinetic parameters of the first step were determined from the DSC curves which enabled the determination of activation energy, pre-exponential Arrhenius factor and order of reaction. This study was however carried out to investigate the effect of pine needle dust briquette on sub-bituminous coal using starch as binder in terms of combustion, emission and thermal degradation characteristics of pine needle-coal briquette.

a: 100% Coal dust briquette.

EXPERIMENTALS

MATERIALS

Sub-bituminous coal was obtained from Onyeama mine, Enugu, Enugu State, Nigeria. Pine needle was obtained from the pine trees at University of Nigeria, Nsukka environs. Cold water starch was procured from the local market at Nsukka. Calcium hydroxide was sourced from a local supplier of chemicals at Nsukka, Enugu State.

Equipments

Digital electronic weighing balance, hydraulic briquetting machine (six rectangular moulds of 8.6 cm × 6.2 cm dimension), local electrical milling machine, 1mm sieve, plastic bowl (for mixing the materials for briquetting), trays, oxygen bomb calorimeter (model: XRIA), TGA 4000 (PerkinElmer), Laboratory Emission Monitoring System (LEMS), briquette stove.

Preparation of coal sample

The sub-bituminous coal sample was sun dried for two days to reduce its moisture content. It was broken into sizes that could enter the hopper of the milling machine using hammer. It was then ground in an electric milling machine.

Preparation of the biomass

The biomass (*Pinus pinaster*) collected was sun dried for ten days to reduce the moisture content of the materials. The material was ground in an electric milling machine.

Preparation of the Briquette Samples

The briquettes were produced in the laboratory of National Centre for Energy Research and Development, University of Nigeria Nsukka, Enugu State. A manual hydraulic briquetting machine with six rectangular moulds of 8.6cm × 6.2cm dimension was used. For the 100% coal briquette, 1% $Ca(OH)_2$ based on the mass of coal was used as the de-sulphurizing agent while 0.5% was used on the binary mixture with pine needle. 2% cold water starch was used as the binder. The pressure was maintained at 5MPa throughout the production.

Table 1: Summary of the mixtures of the various weights of the materials for the production of the briquettes

Briquette Sample	Materials	Weight of materials (g)	Weight of $Ca(OH)_2$ (g)	Vol of water (ml)	Weight of starch (g)
C	Coal dust	500	5	500	100
P	Pine needle dust	500		400	100
CP	Coal dust + Pine needle dust	250+250	2.5	480	100

C= 100% Coal dust

P= 100% Pine needle dust

CP= 50%Coal dust + 50%Pine needle dust

a: 100% Coal dust briquette.

b: 100% Pine needle dust briquette.

c: 50% Coal dust + 50% Pine needle dust briquette.

Physico-chemical composition of the samples

Moisture content, volatile matter content, ash content and fixed carbon of briquette samples were determined using the Pyris Manager Software in the thermogravimetric data analyser (TGA) in line with ASTM D-3173 specifications. The calorific value was determined using Oxygen Bomb Calorimeter.

Combustion characterization via water boiling test (WBT)

This was carried out to determine the combustion characteristics of the briquettes. It measured the time taken for each set of briquettes to boil an equal volume of water under similar conditions. 100 g of each briquette sample was used to boil 100 cm^3 of water using small stainless pot and domestic briquette stove. During this test, other fuel properties of the briquettes including burning rate, thermal efficiency, fire power and specific fuel consumption were determined.

Emission characterization

Emission characterization involving the Laboratory Emissions Monitoring System (LEMS) was used to quantify emission of pollutants from cooking stoves/fuels by collecting, measuring, and analyzing emissions of CO, CO_2 and particulate matter (PM) emitted during combustion.

Determination of thermal stability and composition of materials

The thermal stability and composition of materials were determined using TGA 4000 (PerkinElmer). The various briquette samples were analysed in nitrogen environment at a flow rate of 20 ml/min, pressure of 2.5 bars and heating rate of 10°C/min. To a zeroed thermal balance, samples were loaded and recorded into the equipment using the Pyris manager software. The analysis was then initiated after constant weight was noted using the created heating profile (temperature scan). The thermal responses of the produced composites were examined via a thermogravimetric analyser with the weight loss against change in temperature between the room temperature to 850°C [12].

RESULTS AND DISCUSSION

The results of proximate analyses of the raw material are shown in Table 2.

Table 2: Physico-chemical composition of the fuel briquettes

Fuel sample	Moisture content (%)	Ash content (%)	Volatile matter (%)	Fixed carbon (%)	Calorific value (KJ/kg)
C	1.66	1.19	70.17	27.03	23,471
P	1.20	0.03	49.01	49.76	17,200
CP	0.73	2.33	39.21	57.73	20,336

Table 3: The combustion parameters of the various briquettes

Fuel sample	Burning rate (g/min)	Time required to boil water	Specific fuel consumption (g/litre)	Fire power (watts)	Thermal efficiency (%)

		(min)			
C	3.36	50	173.24	1240	11
P	1.45	35	62.09	383	34
CP	2.96	32	109.67	938	33

Table 4: Emission profile of PM, CO and CO_2 of the various briquettes compared to WHO-AAQS/NAAQS (EPA, 2016).

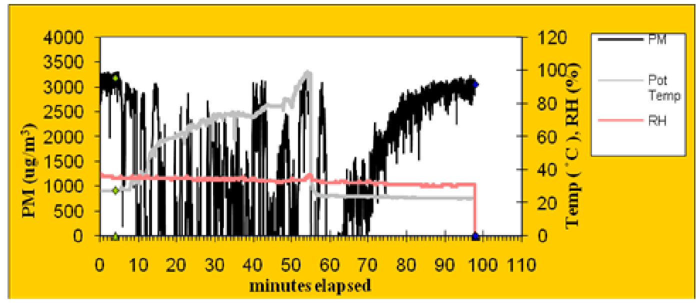
Sample	Particulate Matter (µg/m^3)	Carbon dioxide (ppm)	Carbon monoxide (ppm)
C	3051	80	0.6
P	840	33	0.3
CP	1475	33	0.6
WHO-AAQS	150	600	35
NAAQS	250	-	-

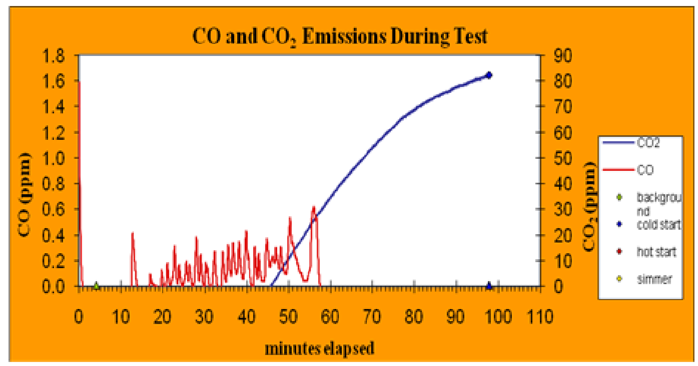
Table 5: Degradation temperature ranges and Peak temperatures from the TGA/DTA Analyses for the briquettes

Fuel Sample	Degradation Temperature (˚C)	Peak Temperature (˚C)	Calculated useful fuel (%)
C	256.30 - 466.90	302.22	80
P	250.32 – 346.62 346.62 – 417.34	321.54 402.87	75
CP	218.43 – 384.07 384.07 – 520.62	347.75 425.89	80

Coal briquette (sample C)

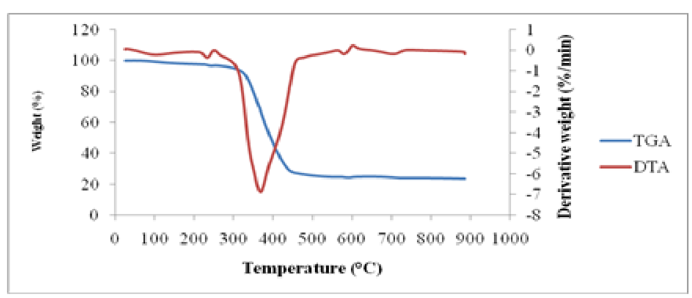
The result of the proximate compositions of the briquettes is presented in Table 2. For the coal briquette produced, a volatile matter content of 70.17% was recorded. This is high and signifies easy ignition of the briquette and proportionate increase in flame length [13]. The high volatile matter content indicates that during combustion, most of the formed briquettes will volatilize and burn as gas in combustion chambers. The percentage of the mineral content represented as the ash was low indicating suitable thermal utilization for the coal sample [14] and large quantities of ash affect the thermal behaviour of the fuel briquette as it constitutes a nuisance to furnace. The fixed carbon for the coal briquette was moderate. Fixed carbon content makes it tend to prolong cooking time by its low heat release as seen in the time required to boil water. The moisture content of the coal briquette was low. Moisture content is a critical parameter for solid fuels. It is vital to the correct operation of boilers and stoves, and for the assessment of calorific value of a fuel [3]. This was evident in the result of calorific value because the moisture content has a direct effect on the calorific value since higher moisture content of fuel samples translates to lower heating values. The high heating value obtained for the briquette produced from coal dust was the highest when compared to other variants (Table 2). This energy value is sufficient to produce heat required for household cooking and small scale industrial applications. Fig. 2 shows the plot of the particulate matter emission for coal briquette as detected by the PM sensor during the WBT using LEMS. The result showed that the concentration of particulate matter emitted during coal combustion was high and in fact higher than the other variants and the World Health Organization Ambient Air Quality Standard (WHO-AAQS) and National Ambient Air Quality Standard (NAAQS) [15] (Table 4). The high particulates could be as a result of the high volatile components and also the environment where the analyses was carried out owing to the fact that the LEMS is an enclosed system which may have led to a buildup in concentration as opposed to when the combustion is carried out in an open or better ventilated environment. The concentration of carbon dioxide and carbon monoxide emitted by coal briquette was the highest when compared to other variants though within the permissible concentration in the atmosphere for 1 hour combustion as proposed by the WHO-AAQS and NAAQS [15]. This implies that even though the concentration of the particulate matter emitted during combustion was high, the briquette is a safe fuel for the end users when exposed under the emitted concentration of CO and CO_2.





The result of the thermal degradation of the coal briquette is shown in Fig. 4.

From the plot, the degradation temperature ranged from 256.3°C to 466.95°C. This implies that at 256.3°C, the coal briquette started degrading until at 466.95°C when most of the useful fuel had been effectively combusted. Therefore, further increase in temperature did not have any effect on the mass of the coal left in the furnace which was now ash. It was then deduced that from the 100mg of the coal briquette in the crucible, about 80% of the fuel was combusted while 20% was suppose to be the ash residue. Again, the TGA plot showed that coal briquette lost all its stability at 466.95°C. The DTA plot again showed that during combustion, the presence of one sharp peak is an indication that

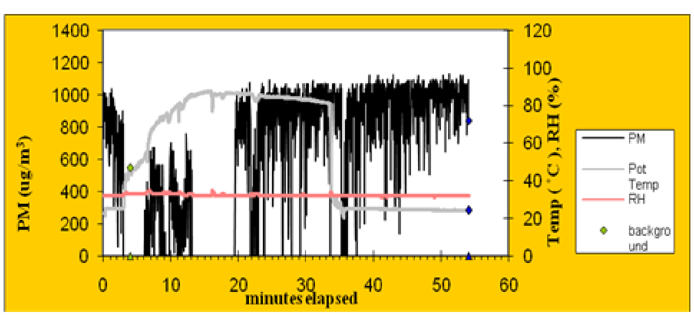


most of the volatile components were driven off at that degradation temperature. The number of peaks indicates the number of active degradation peaks at which the volatiles are driven off. This confirms the report that most coals are decomposed at slightly below 350°C [16]. The sharp peak was seen at the temperature of 325.89°C. The height and sharpness of the peak describes the type of reaction going on during combustion. High and sharp peak gives rise to fast reaction in the combustion chamber while broad and a short peak is an indication of a slow reaction [17]. Therefore, Fig. 4 showed that the combustion of coal briquette in the furnace was fast at that peak temperature resulting to the high and sharp peak.

Pine needle dust briquette (sample P)

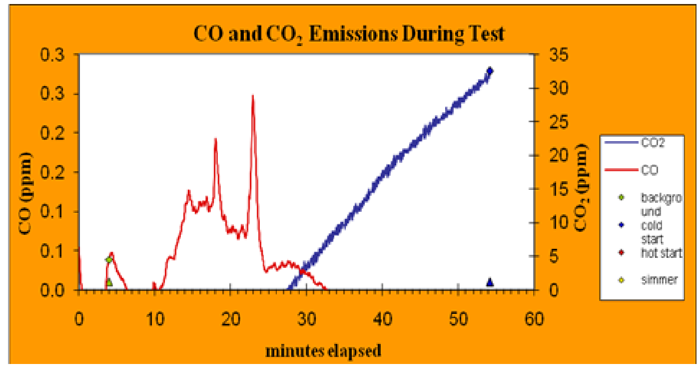
The result of the proximate composition for briquette sample P is shown in Table 2. The moisture content of the pine needle briquette was within the limits of 15% [3] for briquetting of agro-residues. The low moisture content signifies easy ignition and effective combustion of the fuel and also increases the heating value of the briquette. The high heating value calculated for briquette produced from pine needle dust was lower than that of coal but sufficient to produce heat required for household cooking and small scale industrial applications. Even though the calorific value was lower than that of coal, it compared well and better than that from most biomass fuels such as groundnut shell briquette (12,600 KJ/kg) [11], cowpea (14,372.93 KJ/kg) and soybean (12,953 KJ/kg) [18].

The ash content was very insignificant (Table 2). The low ash content indicates that it is suitable for thermal utilization. However, the pine needle briquette had lower volatile matter content. This was lower than the coal briquette and signifies easy ignition of the briquette and proportionate increase in flame length [13. The fixed carbon content was higher than the coal briquette but lower than that of the binary combination (CP) (Table 2). Again, the fixed carbon content shows the tendency of the pine needle to have better cooking properties. Therefore, the fibrous nature of pine needle and the air spaces in the matrix of the briquette enabled it to burn very fast. The result of the water boiling test showed that the burning rate for the pine briquette was faster when compared to other variants. This could be as a result of the ease in combustion which also affected the fire power as it used less fuel to achieve a quicker and more efficient burning when compared with the other briquettes. This translated to the highest thermal efficiency as a result of easy conversion of the heat produced into useful work. For the emissions that were given off during the combustion, the particulate matter concentration was found to be the least when compared to other variants. However, the concentration exceeded the World Health Organization Ambient Air Quality Standard (WHO-AAQS) and Nigerian Ambient Air Quality Standard (NAAQS) [15] as shown in Table 4. The high particulates could be as a result of the chemical composition of the pine needle and also the environment where the analyses was carried out. Combusting the briquette in a better ventilated environment would be expected to give much lower values.



The concentration of carbon dioxide and carbon monoxide emitted by the pine needle briquette were 33 ppm and 0.3 ppm, respectively, as shown in Table 4. This showed that the concentrations of carbon dioxide and carbon monoxide emitted by the pine needle briquette were lower than that of sample C and CP. It was also within the permissible range as proposed by the WHO-AAQS and NAAQS. This implies that the briquette is safe for the end users when exposed under the emitted concentration. Fig. 6 shows the emission profile of CO and CO_2 for sample P.

From the result of the thermal degradation characterization



carried out on pine needle briquette, it was evident that the volatile components were actively driven off at two major temperature peaks from the matrix of the pine needle briquette (Fig. 7).

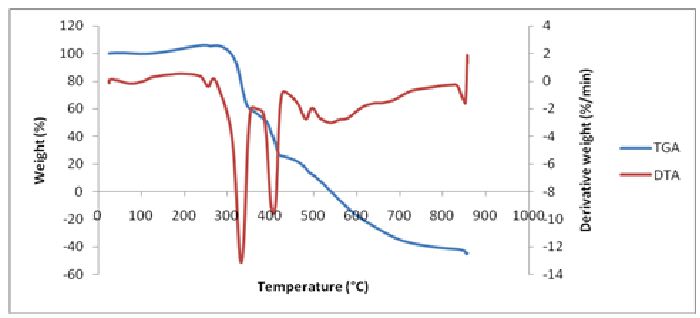
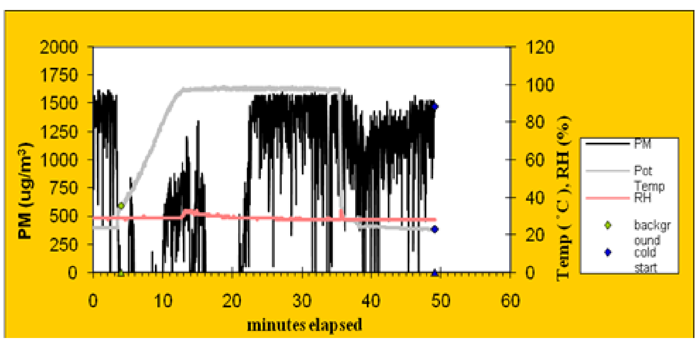


Fig.7 shows the TGA/DTA plot for pine needle briquette. It was evident that there are two prominent degradation peaks at which the volatiles were driven off from the matrix of the pine needle briquette as seen in the thermogram. For the TGA, it was seen that there was a slight increase in weight of the briquette fuel before degradation started. This could be as a result of thermo-oxidation where the sample takes in oxygen and moisture and swells up giving rise to slight increase in weight. The weight loss became effective and started degrading from 250.32˚C to 346.62˚C for the first degradation peak temperature while the second degradation peak temperature started from 346.62˚C to 425.34˚C. The plot also showed that the percentage combustible material in the pine needle briquette was 75% while 25% were assumed to be non-combustible materials. The peak temperature for the first degradation was 321.54˚C while the peak temperature for the second degradation was 402.87˚C. The presence of the two sharp peaks was also an indication that the reaction was fast at those temperatures.

Coal dust + Pine needle dust briquette (sample CP)

The result of the proximate composition and calorific value for briquette sample CP is shown in Table 2. The moisture content of the briquette formed by the binary combination of pine needle dust and coal dust was the least among other variants. The low moisture content signified easy ignition and effective combustion of the fuel and also increased the heating value of the briquette. The high heating value for briquette produced from sample CP showed that the combination produced a briquette with higher calorific value when compared to the single pine briquette again indicating that combining coal with the biomass increased the calorific value of the biomass fuel (Table 2). The energy value is sufficient enough to produce heat required for household cooking and small scale industrial applications. The ash content was moderately higher when compared with the other variants. However, the combination produced a briquette with lower volatile matter content signifying that the combination produced a briquette with low amount of combustible materials. Due to the fibrous nature of the pine, the combination gave a briquette which burned faster than the single coal. This was evident as the time required for the briquette to boil the same quantity of water was shorter when compared to the time for briquette sample C thereby giving rise to a briquette with moderate burning rate, improved fire power and good equivalent fuel consumption when compared to the single pine briquette. Again, the blending of pine with coal increased the thermal efficiency of the briquette when compared to the single coal. The concentration of carbon monoxide and carbon dioxide was found to be lower than that of the coal briquette but slightly higher than the pine briquette. This indicates that blending pine needle with coal reduced the concentration of CO and CO_2 emitted. When compared to the WHO-AAQS and NAAQS in Table 5, it is evident that the concentration of CO and CO_2 were lower than the standard. The concentration of the particulate matter (PM) was higher than the stipulated standards and that of the pine briquette though lower than that of coal briquette. This also shows that combining pine needle dust with coal reduced the PM emissions.



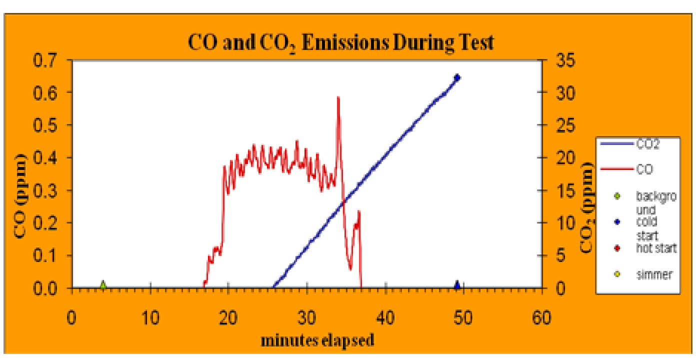
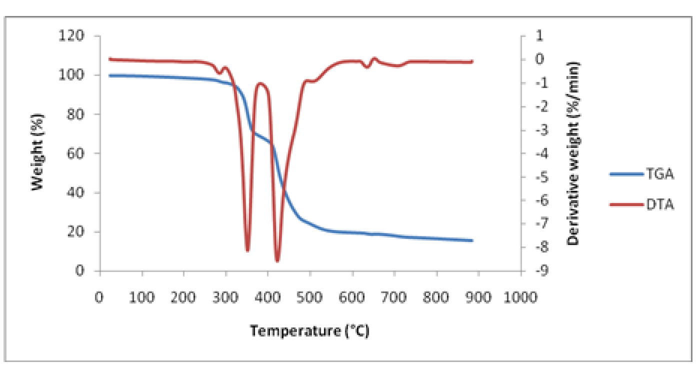


Fig.10 shows a plot of TGA/DTA analysis for the binary combination of coal dust and pine needle dust to produce



briquette (CP). The result of the TGA/DTA showed that for the briquette CP, two degradation peaks were present in the fuel sample. The degradation temperature for the first peak started from 218.43˚C to 384.07˚C and 384.07˚C to 570.62˚C for the second peak. Therefore, the briquette sample CP lost its thermal stability around 570.62˚C.

The addition of coal to pine needle obviously increased the stability of the briquette during combustion and further increase in the temperature above 570.62˚C did not have any effect on the mass of the briquette fuel. The percentage useful fuel in the briquette sample CP was deduced to be 80% while the remaining 20% were suppose to be non-combustible materials. The two peaks that were seen in the DTA curve indicated that there were two prominent degradation peak temperatures at which all the volatiles were driven off in the briquette. The first peak temperature was at 347.75˚C while the second peak temperature was at 425.89˚C. Blending coal with pine needle produced a briquette with higher thermal stability when compared to the single pine needle briquette alone as well as a briquette with more useful fuel compared to the single pine briquette. This indicates that combining pine needle dust and coal dust for briquette production has better combustion and emission characteristics than using either of the fuels alone.

CONCLUSION

The results of the proximate compositions, calorific values, combustion parameters, emission profile and thermal degradation properties has shown that combining biomass with coal had very positive impact in terms of heating value. Again, coal dust briquette was the most stable briquette while pine needle dust was the least stable during combustion and blending coal with the biomass increased the thermal stability and the useful fuel produced. The combustion analysis also showed that pine needle dust briquette was the most efficient during burning while coal was the least. However the blending of the biomass with the coal increased the thermal efficiencies of the briquettes. Again, the burning rates, the specific fuel consumed and the time to boil the same quantity of water was enhanced by the blended briquette. However, the fire power of the coal was highest and the blending of coal with the biomass increased the fire power of the briquettes. As regards to the environment, it was found that blending the biomass with coal reduced the concentration of the harmful emissions evolved during combustion.

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