Fixed Bed Combustion of Biomass: Particulate Matter Mitigation by Optimising Temperature and Fuel Particle Size

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Abstract. Experimental results are presented on the particulate matter emissions from a fixed bed combustion reactor chamber combusting two types of ambient dried biomass fuels, six different particle sizes (0.044-0.149 mm) in seven different temperature zones (600-1200 º C). The fuel was ground into various particle sizes and the temperature of combustion was varied for investigation on the emission due from the various parameters. Measurements were made for particulate matter (PM) during the whole phase of combustion by a portable soot analyzer. The PM investigated here is total catch that includes solid particles of elemental carbon and fuel and condensed organic compounds due from incomplete combustion which are less than or equal to 10 µm in aerodynamic diameter. The fuel was ground by a grinder and sieved into different sizes by a shake sieve with various mesh sizes. It was found that the PM emission from both biomass fuels was significantly dependent on the temperature of combustion which in turn dictated the residence time in the combustion chamber. The mean PM mass emissions from wood and peanut shell were established. The optimum combustion temperature was identified to be 900 ºC attracting PM mitigation of up to 63%. The least PM producing particle size for peanut shell and wood fuel was determined to be 0.149 mm combusting at 1200 º C and 0.074 mm combusting at 600 ºC respectively with capacity to mitigate PM production by a maximum of 30-49%. However the effect of the two parameters was established to be mutually dependent. The time taken for complete combustion reduced steadily with the increase of the temperature from 360 seconds at 600 º C to 150 seconds at 1200 º C.

1. Introduction
Solid biomass has been used for centuries especially in domestic and industrial energy supplies. Due to the greenhouse gases effects on the environment, there is intense interest on measures resulting in less pollution, making biomass use more attractive albeit its particulate matter (PM) challenges that have caused serious health concerns, with fine particles of below 1 µm pausing the greatest risk to human health [1]. Going forward the PM inventory from biomass is bound to increase. There is need for a comprehensive knowledge on biomass feedstock on both physical and chemical characteristics [2] especially to inform mitigation of PM production. While wood is the most predominant of all biomass fuel, wood combustion is associated with high emissions of polycyclic aromatic hydrocarbons (PAH) among other organics which are known to be both carcinogenic and mutagenic [1, 3, 4].
Extensive research is being undertaken on the combustion of various agricultural by-products and other unconventional fuels like maize cobs, date stones, palm stalks and grasses among others [5-9, 17]. Different systems are being used in combusting the fuel, for pulvurised fuel systems the fuel particles are milled to a size between 10-1000µm in an effort to optimise the combustion process that is partially controlled by residence time, turbulence and temperature [2, 10], these particle sizes are the focus of this paper. It is also well established that raw biomass has a high content of moisture and even after some time of ambient drying depending on the weather, there remains about 15-20% of moisture. When more drying is not achieved the fuel loses a lot of energy through latent heat of evaporation significantly decreasing the efficiency, alternatively, there is immense energy consumed in drying the fuel to the required moisture levels before usage and the process is energy intensive calling to focus the optimal practices[12]. There is therefore more interest on using unprocessed or semi-processed fuels.

A solid fuel is basically composed of volatile material which is usually predominant in biomass fuels and other elemental compositions like carbon and nitrogen among others. The volatile material burns as a gas and exhibits a visible flame whereas the fixed elements like carbon burns without flame as a solid form [10]. Based on the relationship between chemistry and heat and mass transfer during particle conversion, fuel particle size has a major effect on the emissions [2].

There is also major interest being directed towards co-firing of biomass and coal as a way of reducing the greenhouse gases production [11, 15]. For co-firing as well the fuel particle size and temperature are principal parameters.

In this paper the optimal temperature for combustion and particle size especially for pulvurised systems are investigated and the relationship between particle size, temperature, residence time and particulate matter emissions is established based on experimental results. Finally the PM mass emissions per unit mass from the two fuel samples is determined. The determination of which shows that the combustion of biomass in optimal temperature and particle size can largely mitigate the production of PM.

2. Experiment Materials and Set-up

2.1. The fuel

Peanut shells are generally herbaceous biomass fuel [14]. The chemical composition of raw peanut shells is determined to be lignin (about a third of the fuel mass), cellulose (approximately one third to half of the fuel mass) and other minimal compositions of protein, ash and moisture. [21]. The shells have a fibrous ‘skeleton’ supporting a cellulose-lignin layer. A substantial proportion of fibres in peanut shells (up to 70 wt. % [21]) significantly affects the texture of fuel particles and consequently, devolatilisation and combustion behaviour of the biomass fuel.

The peanut shells were shred into six different sizes, the largest being 0.149mm and the smallest being 0.044mm. The bigger particles took wafer like flaked dimensions while the fine particles often appeared in an agglomeration of particles that stuck together to form a circular figure especially enhanced due to the shaking process through the mesh wire.

Wood cells are composed of cellulose (40% to 50%), hemicellulose (15% to 25%) and lignin (15%-30%) [13]. The wood was ground into six different particles of similar size to the peanut particle sizes. Grinding wood results into single fibrous particles that are not clustered unlike peanut shell.

Table 1 shows the ultimate and proximate analysis as well as the heating value of both fuels grown in China used in this work. It can be seen from the proximate outcome that the volatile matter from both fuels is significantly high accounting for more than two thirds of the fuel content. There is a low proportion of fixed carbon especially for wood, a rather low proportion of fuel ash for peanut shell but significantly low for wood, the moisture content for both fuels is also quite low for this ambient dried biomass fuel.
### Table 1. Table Showing Proximate and Ultimate Analysis

| Fuel       | (M)%  | (VMad)% | (Amad)% | (FCad)% | (C)%  | (H)%  | (S)%  | (N)%  | (O)%  | Heat Value(kcal/kg) |
|------------|-------|----------|----------|----------|-------|-------|-------|-------|-------|---------------------|
| Wood       | 11.29 | 80.79    | 2.68     | 5.24     | 38.76 | 4.95  | 0.18  | 1.37  | 40.82 | 4969.00             |
| Peanut shell| 9.75  | 73.72    | 3.43     | 13.10    | 37.44 | 4.65  | 0.07  | 1.11  | 43.56 | 5172.00             |

2.2. Experimental Setup

This research was to determine the effect of temperature and fuel particle size on emission of PM per unit mass of fuel combusted for the subsequent two types of biomass; common wood and peanut shell. Investigations of the combustion process were carried out in an electric fixed bed reactor with capability for a constant pre-determined temperature and air flow for a stable and complete combustion. The measurement of PM concentration per metre cubic of gas was determined using a portable Foedisch PFM 92K portable soot analyser with a stainless steel probe with a pre-amplifier. The measuring principle is dependent on the friction electric sensor with a measuring range of 0.1-1000mg/m³. Investigations on the combustion process were carried out for the parameters shown in table 2.

### Table 2. Table Showing the Parameters Onsidered in the Experiment

| Temperature(℃) | 600,700,800,900,1000,1100,1200 |
|----------------|----------------------------------|
| Particle size (nm) | ≥0.149; ≥0.105; ≥0.088; ≥0.074; ≥0.053; ≥0.044 |
| Air flow rate | 1200ml/min |
| Air mixture | O₂:21%, N₂:79% |

![Figure 1. The experimental set.](image_url)

A: Oxygen  
B: Nitrogen  
C: Pressure Valve for Oxygen  
D: Pressure Valve for Nitrogen  
E: Gas Mixing Chamber  
F: Combustion Chamber  
G: Ceramic Boat with fuel sample  
H: Thermal Regulator  
I: Flue gas  
J: PM measuring device  
K: Flue gas  

After reaching the predetermined temperature in the combusion furnace at the set airflow, a ceramic boat with a predetermined mass of sample fuel was introduced into the combustion zone and the combustion instantly started. In that moment both readings were concurrently taken by the flue gas analyser and the portable soot analyser. After a period of time the concentration of the flue gases in the exhaust stream decreased to normal at which point the experiment was terminated. All emissions indications were recorded starting from the time when the samples were introduced into the
combustion zone until the moment where no emission indicated. The recorded concentrations were used to determine the outcome. All samples were preserved under the same conditions at room temperature. To enhance result confidence, it was necessary to repeat measurements a number of times under similar conditions. All pollutant measurements were done at least twice; a mean emission value was calculated from results obtained. Typical emission curve for PM evolution can be seen in Fig. 2. The values (in mg per gram of combusted fuel) for Particulate Matter were derived from the following equation:

$$W_z = \frac{q.t.c_p}{m_f}$$

where $W_z$ is the mass of pollutant in mg.g$^{-1}$ of fuel, this measurement is taken by the portable soot analyser, $q$ is the flowrate of gas (O$_2$ and N$_2$) supplied to the combustion chamber in m$^3$.s$^{-1}$ while $t$ is the period of time considered in seconds. $C_p$ is the PM concentration during combustion in mg.m$^{-3}$ that is was recorded once per second during the experiment. Finally, $m_f$ is the mass of fuel sample in grams.

3. Results and Discussion

3.1. Residence Time

The mean time taken for a sample of approximately 0.030 grams to combust entirely was determined to be 360 seconds at 600°C but steadily decreased to a mean of 150 seconds at 1200°C. The biomass considered in this experiment had a high Volatile/ Fixed carbon ratio which dictates that the dominant form of combustion is gas phase oxidation of the volatile species. Volatility of which is influenced by both fuel particle size and combustion temperature both considered here [18]. Smaller particles in this case release more volatiles rapidly due to the increased surface area for fuel oxygen interaction and the higher temperatures of combustion considered here compel majority of the combustible fuel to be released as volatiles while the lower temperatures considered here favor the formation of char. This serves to explain the decrease in residence time; that as temperatures spiral upwards the combustion is practically almost finished at the end of the release of the volatiles which are the majority of the combustible fuel.

There is a sharp PM peak or sometimes multiple peaks at the beginning of combustion and towards the end of the process with changeable heights as the first peak could be higher and wider or lower. The multiple peaks indicates that there are more than one process taking place which sometimes overlap and sometimes subsequent one another. At the start of combustion the release of moisture and volatile evolution pursued by combustion of the volatiles can succeed one another in high temperatures hence indicating the multiple peaks. Later in the burning process the char combustion largely occurs as char oxidation which is accomplished through gas-solids reactions [18] hence multiple peaks as well can be formed due to the presence of more than one gas in the reaction.

![Figure 2. Figure Showing the PM Indication at 600°C And 1200°C.](image-url)
There is also an observation indicating a significant gap between particles concentration points accounting for more than 70% of the fuel combustion residence time. When fuel is introduced into the combustion zone, emissions increase profoundly due to the release of primary volatile organic compounds [20], there is an ensuing charcoal forming stage that is quite low in emissions whose time can identify with the low or no particle indication observed, after which the charcoal combustion emissions are recorded towards the termination of the combustion process.

3.2. Temperature and Particle Size

1) Peanut shell

In this investigation there is a twin effect of temperature and particle size, of which temperature seems to have a domineering effect. There is a strong indication that the increase of temperature leads to less PM formation during VM combustion for peanut shell(Fig.3). PM is indicated to be more during char combustion and less during VM combustion except for combustion occurring at 700ºC where PM was leading during VM combustion(Fig.5). At 900ºC, the lowest PM indication during both VM and char combustion was recorded, this observation has high similarity with 1200ºC, where the PM indication was also quite low. It has been established that combustion occurs at three major levels with adsorbed water being driven out between 57-92ºC, organic matter combustion between 200 and 650ºC and burning of residual char between 650 and 850ºC[19]. This strongly indicates that below 900ºC there is a high probability of soot production due to incomplete combustion which boosts the PM formation. This supports the findings that 900ºC is the optimal combustion temperature.

Figure 3. Showing the PM yield during VM combustion.

The mean PM yield from peanut shell combustion was 18.200±9.200 g.kg⁻¹. As shown below; the data collected at temperature zones 600 to 800ºC (Fig.5) had a huge difference between the PM indicated during VM combustion and char combustion due to the effect of particle size at these temperatures which encourage volatilization of fuel and slow char combustion informing some huge standard deviation in the data, additionally, the data is from six different fuel particle sizes. There is research informing the contribution of biomass to the inventory of ambient PM for PM₁₀ and PM₂.₅ but there is no data related to the combustion of peanut shells. The current AP-42 document from the Environmental Protection Agency (EPA) emission factors corresponding to wild fires and fire place PM is 8.500g.kg⁻¹ and 17.300 g.kg⁻¹ [20], the same research findings put PM₂.₅ production from below average quality rice residues at 12.950±0.300g.kg⁻¹ both of which are in our neighborhood.
Fuel particle size is a governing factor in PM emission, decreasing the particle size increases the formation of PM however there is need to consider the impact of the micro-particle sizes used in pulverized combustion systems [22]. From observation there is significantly less PM indication from 900°C to 1200°C for all the particles involved in this investigation (Fig.5). Considering 900°C and 1200°C where there is occurrence of lowest PM and at a superimposed pattern of occurrence, 0.149mm, 0.105mm and 0.088mm are the lowest PM indicators in ascending order (Fig.5).

2) Wood

The lowest PM yield was obtained at 900°C while the highest was recorded at 1100°C with a yield increase of 200% (Fig.8). At 600°C and 700°C the PM yield was leading at VM combustion, beyond which the major PM yield is indicated during char combustion(Fig.8). The mean PM yield from wood was determined to be $13.062 \pm 5.840 \text{ g.kg}^{-1}$ of wood fuel. Research findings put the PM$_{2.5}$ emission from different kinds of biomass as being from 4.000g.kg$^{-1}$ to just above 40.000g.kg$^{-1}$of fuel from different kind of fires; wild fire, residential fire and agricultural fires [16]. The EPA, AP-42 document puts the emission factor for residential wood PM due from combustion at between 9.800g.kg$^{-1}$to 15.300 g.kg$^{-1}$ [20]. Different firing techniques are bound to tone the PM yield differently due to the varying combustion efficiencies.
Particle size seems to play a more defining role in wood fuel as opposed to peanut shell. During VM combustion the effect of particle size is well observed at 600°C, 700°C, 900°C and 1000°C (Fig. 6). There is a strong pattern indicating an increase in PM as the particle size decreases (Fig. 6). During char combustion at 600°C, 900°C and 1200°C, the particle size impact is neutralised, nevertheless there is a weak linear increase of PM as the temperature increases during wood char combustion (Fig. 7).

4. Conclusion
Two biomass fuels; wood and peanut shell were combusted in this experiment. The total PM associated with both was significantly affected by the temperature of combustion. 900°C was identified as the optimal temperature for both wood and peanut shell combustion, at this temperature the lowest PM was indicated for both fuels respectively. The time of combustion for both fuels had an inverse relationship with the temperature of combustion. There was a strong linear decrease of PM indication during VM combustion for peanut shell and a weak one for wood. Generally, some combustion temperatures considered in this experiment serve well to neutralize the particle size impact both during VM and char combustion leading to relatively less PM yield. Due to the complex relationship and joint impact of temperature and fuel properties on PM yield, the impact of particle size on PM yield was not clearly realized. A bigger difference between the particle sizes would help magnify the link between PM and particle size, nevertheless a clear output on effect of temperature on PM yield was achieved.
5. References

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