Original Paper

Special articles: Asian Conference on Biomass Science I

特集：アジアバイオマス科学会議 I

Comparative Real-time Assessment of Particulate Matter Emissions in Rice Husk Combustion

Emmanuel Owoicho ABAH^{*1}, Kazuma IWAI^{*1}, Kai SAKURAI^{*1}, and Ryozo NOGUCHI^{*2†}

(Received January 15, 2018)

Biomass combustion is the most traditional method for its utilization to obtain heat energy as a global source. However, combustion of biomass fuels has been associated with air pollution and emission of toxic pollutants such as particulates, if sufficient appropriate technology was not used. This study focuses on the comparative assessment of particulate matter (PM) of 10, 4, 2.5 and 1.0 μm . Real-time measurement of particulate matter was conducted in laboratory scale, using a Dust-track II aerosol counter and a Yamato F100 fixed bed combustion chamber, attached with a fabricated heat exchanger for reducing the temperature of the exhaust point for sampling. Combustion experiment was conducted for 3 min duration for each 1 g sample of rice husk for each temperature category (600, 700, 800, 900 and 1000 °C). A mean value of 5 tests for each of the temperature category was carried out. Maximum PM_{10} mass concentration was recorded at 600 °C and 1000 °C as 150.0 mg/m^3 and 71.53 mg/m^3 respectively, compared to 121.6 mg/m^3 and 87.6 mg/m^3 of $\text{PM}_{2.5}$. However, $\text{PM}_{2.5}$ mass concentration for temperatures of 700 °C, 800 °C, and 900 °C, was apparently higher than that of PM_{10} .

バイオマスの燃焼は、熱エネルギーを得るため世界的に最も伝統的な方法である。しかしながら、バイオマスの燃焼による熱エネルギーの利用において、適正かつ十分な技術を使用しなければ、大気汚染や微粒子などの有害汚染物質の排出などを引き起こす。本研究では、水稻籾殻の燃焼に伴って発生する 10, 4, 2.5 および 1.0 μm の粒子状物質 (PM) の比較評価に焦点を当てた。粒子状物質のリアルタイム測定は実験室規模で実施され、籾殻燃焼のために固定床燃焼チャンバー (Yamato F100, PM 測定のためにエアロゾルカウンター (Dust-track II) が使用された。サンプリングを行う排気ガス排出口の温度を下げるために、熱交換器の製作と取り付けを行った。燃焼の各温度区分は、600, 700, 800, 900 および 1000 °C とし、籾殻サンプル 1 g あたり 3 分間の燃焼実験を行い、それぞれの燃焼温度について 5 回の平均値を採用した。燃焼温度 600 °C と 1000 °C において、 $\text{PM}_{2.5}$ の最大質量濃度は 121.6 mg/m^3 および 87.6 mg/m^3 、 PM_{10} の最大質量濃度は 150.0 mg/m^3 および 71.53 mg/m^3 が測定された。しかし、燃焼温度 700, 800 および 900 °C の $\text{PM}_{2.5}$ 質量濃度は、 PM_{10} よりも明らかに高かった。

Key Words

Particulate matter, Size fractions, Emissions, Concentration, Temperature, Combustion

1. Introduction

Open air burning of biomass fuels leads to environmental contamination, health risk and poor visibility problems due to the emission of pollutants¹⁾. Biomass burning in inefficient cookstoves, open fires, agricultural fires and forest fires, among others, account for 85% of

particulate matter emissions and almost all emission of Sulphur and nitrogen oxides²⁾. A significant number of pollutants are emitted during a biomass combustion process. The critical pollutants emitted include carbon monoxide, carbon dioxide, nitric oxides, hydrocarbons, polycyclic aromatic hydrocarbons (PAHs) and particulate matter (PM), among others³⁾. Most PAHs and particulates form part of a category of toxic pollutants, known as carcinogens. Their formation is multifaceted and depends on the temperature in the combustion chamber. $\text{PM}_{2.5}$ from outdoor air or biomass sources such as wood, has been found to have an impact on health⁴⁾. $\text{PM}_{2.5}$ is the most studied form of air

*1 Graduate school of life and environmental science,
University of Tsukuba
1-1-1, Tennoudai, Tsukuba-shi, Ibaraki 305-8572, Japan

*2 Faculty of life and environmental science,
University of Tsukuba
1-1-1, Tennoudai, Tsukuba-shi, Ibaraki 305-8572, Japan

† Corresponding author: noguchi.ryozo.gm@u.tsukuba.ac.jp

pollution and is associated with a broad range of diseases in many organ systems^{5) 6)}.

The type of combustion system significantly influences PM emissions from such operations. These combustion systems are group into natural draught systems and enforced draught systems. The natural draught systems include fireplaces, wood stoves, chimney stoves. Transportation of combustion air and flue gas in such set up is only by natural draught. Therefore, there is limited or no room for optimization of the combustion process (the mixing of the combustion air and the flue gas), which is critical to reducing the PM emissions. The enforced draught systems are setups where there is total control of the supply of the combustion air as well as the transport of the flue gas. These methods include all modern combustions systems. The use of pellets, wood chips, and logwood boilers are based on this principle. Combustion in these systems are automatically controlled and can be optimized. Thus, PM emissions can significantly be reduced. Many studies have been conducted on measurement and gravimetric analysis of PM emissions, with little to none on specific areas such as real-time measurement of PM from rice husk combustion. Also, another motivation for this research was the need to proffer solution to the frequent burning of rice husk in the open air among rural communities in Nigeria. This study focuses on the comparative assessment of particulate matter (PM) of 10, 4, 2.5 and 1.0 μm , to determine the worst-case scenario of particulates emissions from rice husk combustion.

2. Experimental procedure

The experimental setup of this study (Fig. 1) consists of three major components; this includes the Yamato F100 combustor, a tubular heat exchanger, and the dust track II analyzer. The Yamato F100 combustor has a temperature range of 0 - 1200 °C. The combustor can be pre-set to any temperature within its range, by using the control buttons. The tubular heat exchanger was specially designed and fabricated for this study, using the Linear Mean Temperature Differential (LMTD) principle. Water is used as the coolant and is connected to the cooler as shown in the figure. The lowest possible temperature the cooler can be pre-set is -5 °C. However, for this experiment, the cooler was set between a temperature range of 20 °C - 23 °C. The reason behind this was to minimize moisture condensation on the inner wall of the exhaust tube. Consequently, avoiding much particle loss through absorption and deposition.

The dust track analyzer is a real-time particulate matter sampling instrument. It uses a battery that can be

Fig. 1 Experimental setup

charged using power from the mains. It is recommended that the battery be fully charged before its usage for experimental sampling. The dust track II (handheld) is a single channel photometer. Thus, size-selective inlet conditioners (impactors) were used to cut down the particle size entering the inlet. It has a standard air flow rate of 3 L/min. Different impactors were used for the various particle sizes to be measured. Impactors for PM 10, 4.0, 2.5, and 1.0 μm correspond to particulate sizes of 10, 4.0, 2.5, and 1.0 μm . PM1.0 impactor has the narrowest inlet. These impactors have a D-50 cut point, meaning; 50% of the particles entering the inlet passes through and the other 50% impact on the plate. As the velocity increases due to the narrower inlet, the mass concentration of particles entering the inlet decreases. Thus, enabling the target particles to follow the airstream around the flat plate of the impactor and into the instrument. 2 - 3 drops of the impactor oil was applied on the impactor plate to trap the undesired particles impacting on its surface, thereby allowing the impactor to be used for a longer time.

Table 1 shows the summarized experimental conditions of the experiment and other relevant parameters.

Table 1 Experimental conditions

Material	Rice Husk
Feedstock loading	1 g/sample
Target temperature	600-1000 °C
Residence time	3 min
Flow rate of dust track analyzer	3 L/min
Target PM	10, 4.0, 2.5, 1.0 μm

3. Results and Discussion

Fig. 2 and three below, presents PM_{10} and $PM_{2.5}$ concentrations respectively, from a 3-minutes combustion experiment. The maximum mass concentration of PM_{10} and $PM_{2.5}$ was recorded at 600 °C. These could be explained by the following; combustion process consists of three crucial stages namely, the ignition stage, the flaming/combustion stage, and the burn out stage. At the start of the combustion process, which is the ignition stage, the oxygen content of the flue gas reduces as the furnace temperature increases. However, if the oxygen level is considerably high while the furnace temperature is low, then it becomes difficult to achieve proper burn-out, thus leading to higher emissions. This could be the case as the air flow in the Yamato F100 combustor is constant at 1.5 m/s. However, as the combustion process stabilizes, the oxygen level in the flue gas is maintained, while the combustion temperature increases, thereby ensuring efficient burn-out. At this stage, particulates emissions are significantly lower as compared to the ignition stage. From the graph below (Fig. 2 and Fig. 3), the particulates emission peaked at the early stages of the combustion process (25-50 sec) and decreased as burn-out phase tends toward completion. Ref. 7) reported that most of the emissions from a one-cycle combustion process occurs in the ignition stage⁷⁾.

Fig. 4 below, presents the peak concentration of PM size fractions over a three-minute combustion period under different temperature category. As shown in the figure, the rate of particulates emission peaks at the initial combustion stage which is characterized by a lower temperature of the combustion air. However, the particles concentration decreases as the temperature increases up to 800 °C. In previous biomass combustion experiment⁸⁾, particles yield

Fig. 2 PM_{10} concentration against time

Fig. 3 $PM_{2.5}$ concentration against time

Fig. 4 Effect of temperature on mass concentration and size fractions of $PM_{10-1.0}$

increases with temperature and peaks at a temperature of 500 °C. Further temperature increases of up to 1000 °C, resulted in a decrease of the particulates. These apparently agree with our result, as the trend is similar. Although the temperature category at which we recorded maximum particulates concentration was 600 °C, as compared to Ref. 8), the particulates size fractions all have a similar trend. It is necessary to state here that the dust track II analyzer recorded this values in real time. Five repeated tests were conducted under the same conditions for each particle size, and the average value was used in plotting the graph.

Three fundamental phenomena could have influenced the recorded mass concentration in both ways. These are; Thermophoresis deposition, coagulation of fine particles, and gravitational settling deposition. Thermophoresis is due to the temperature gradient in the surrounding gas,

thereby attracting particles towards the lower temperature direction. It majorly influenced the transport loss of submicron particulate matter⁹⁾. The significant temperature difference of the emission effluent and the walls of the emission channel because of the heat exchanger implies that thermophoresis may have affected the particulates mass number as a heat exchanger was used to cool the emission before entering the inlet of the sampler. It could be speculated that thermophoresis might partially be the reason behind the increased mass concentration of PM_{2.5} due to increasing temperature (900 °C - 1000 °C). However, some particles may stick to the wall of the emission channel, thereby reducing the total mass number of particles detected by the dust track measuring tool.

Coagulation of fine particles involves the collision of ultra-fine or fine particles due to their relative motion, thus sticking together to form large particles¹⁰⁾. Temperature affects the coagulation process. When the temperature of flue gas increases, the flue gas velocity also increases. Consequently, the relative motion of the flue gas particles is enhanced, thereby aiding the particle coagulation process. In the figure above, particulates size fractions decrease with increasing temperature to 800 °C, signifying that, some of the particulates may have been merged and deposited¹¹⁾. They suggested in this experiment that ultra-fine particles collide and agglomerate to form fine particles. Bed particles are likely to agglomerate when the cohesive force between the particles is strong enough to compete with other acting forces such as gravitational, drag¹²⁾. Coagulation is also influenced by the concentration of particles in the flue gas. This principle is the Brownian motion phenomenon.

Gravitational settling deposition occurs because of gravity, and it has more impact on coarse particles. However, as the sampling temperature decreases, particles losses due to gravitational settling increases due to a decrease in velocity of the flue gas. Therefore, it is accountable for the partial loss of particulates before arriving at the entry point of the dust track analyzer. It can be explained that the impact of combustion temperature varies lightly among the PM size fractions. Other research⁵⁾ supports this view, whereby a similar result was reported which explicitly stated that the effect of sampling temperature is notably different among PM₁₀₋₁₀ µm.

4. Conclusion

This study presented the comparative real-time assessment of particulate matter size fractions (PM₁₀₋₁₀) from rice husk combustion. The experimented parameters showed the significant effect of temperature on PM emissions. From the results, the maximum mass

concentration of the PM size fractions was obtained at the initial combustion stage, characterized by a low temperature of combustion air. Interestingly, PM emissions at a temperature of 700 – 800 °C recorded the lowest mass concentration. Previous research has shown that combustion of rice husk at a temperature of 700 °C produces the best quality of rice husk char for use as a soil supplement. Therefore, rice husk can be used as a combustion fuel for the parboiling and drying process of paddy, while the byproduct (rice husk char) can be directly used as a soil supplement. This way, particulates emission is greatly minimized, and other farm emissions due to the use of chemical fertilizers are reduced. Therefore, boiler system should be designed in such a way that the combusted rice husk is continuously removed from the combustion area every two minutes. These help in preventing the crystallization of rice husk ash.

Acknowledgment

This study is sponsored by the Japanese government under the African Business Education Initiative scholarship (ABE Initiative).

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