The behavior of suspended particulate matter emitted from the combustion of agricultural residue biomass under different temperatures

Q. Wang, S. Itoh, K. Itoh, P. Apaer, Q. Chen, D. Niida,
N. Mitsumura, S. Animesh, K. Sekiguchi & T. Endo
Graduate School of Science and Engineering, Saitama University, Japan

Abstract

There are large quantities of waste rice husk and straw estimated at around 3.9 million tons as biomass waste every year in Japan. Air pollutants emitted from exhaust gases of rice husk incineration lead to environmental damage, not only because of the influence on global environment and climate, when released into the atmosphere, but also on human health due to local air pollution. Therefore, it is necessary to effectively utilize waste rice husk and straw to reduce air pollutants. In recent years, there has been an increasing demand on the utilization of unused biomass instead of fossil oil fuel in combustors for farming-greenhouses' heating during the winter season. The increasing demand will increase the running costs. In general, since these combustors are small in size, there is a lack of regulations or laws (e.g. The Air Pollution Control Act and The Waste Disposal and Public Cleaning Law) in operation for their air pollution control. So far, small size combustors are characterized by their simplicity of structure and low costs. However, they emit visible black carbon (elemental carbon) due to their poor combustion performance. In this study, the possibility of the substitution of fossil fuel by waste rice husk and rice straw is investigated in laboratory model combustion experiments. The emission behavior of harmful air pollutants emitted from rice husk and straw combustion is evaluated by measuring carbonaceous and ionic composition of suspended particulate matter in the exhaust gases. From the analytical results, particulate mass concentrations were found reduced substantially at high temperature combustion. From the results of this study, it can be suggested that stable combustion performance

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under suitable conditions is needed in order to control less air pollutants emitted from biomass fuel although small size combustors are still not regulated.
Keywords: rice husk and rice straw, small size combustors, combustion conditions, carbonaceous, ionic and metallic composition, $PM_{2.5}$.

1 Introduction

Global warming has become increasingly evident in the global climate. Combustion of fossil fuel is generally admitted as the main cause for global warming. However, the use of fossil fuel is expected to increase in the future because of economic development and growth of population in developing countries [1], hence, the only solution is zero-emission technology, that is, to reduce all possible emissions produced by human activities to zero [2]. In order to achieve zero-emissions, it is important to apply a technology to utilize all unused biomass [3; 4].

Currently in Japan agriculture and forestry produce biomass residues from where a very small amount is used, and unused biomass is mostly being incinerated for disposal, due to its high cost of collection, transport, and storage and also the needs of energy that it implies. Moreover, urgent countermeasures are required to reduce the air pollution from illegal waste biomass incineration. It is estimated that only in Japan around 3.9 million tons of waste rice husk and rice straw, which is the most common agricultural residue in the country, are wasted every year. Additionally, since rice is the staple food and regular part of the diet for almost half of the world population, an effective utilization of waste rice husk and straw as biomass fuel would be an important countermeasure to global warming. In recent years there is an increasing demand on the utilization of unused biomass instead of usual fossil oil fuel combustors for farming-greenhouses heating during the winter season. This increase in the demand will make prices to increase. In general, these combustors are small in size [5] therefore existing regulations do not apply (e.g. the air pollution control act and the waste disposal and public cleaning law). So far, small size combustors are characterized by simplicity in their structure and low costs, however, visible black smoke and pollutants are emitted due to the poor combustion performance and the lack of regulations [6, 7]. In this study, the potential use of waste rice husk as biomass fuel is investigated based on laboratory model combustion experiments. Firstly, the chemical composition of agricultural waste rice husk and straw were analyzed thus investigating its combustion characteristics. Then, the air pollutants emitted from waste rice husk and straw combustion were measured by sampling suspended particulate matter and gases in the exhaust under the different combustion conditions. The possibility of reduction of these harmful substances in $PM_{2.5}$ and the exhaust gases were also investigated.

2 Experimental methods

2.1 Composition analysis of the rice husk and straw

In this study, rice husk and straw composition (Nigata Prefecture of Japan) were analyzed. The proximate and ultimate analyses of their samples were carried out according to the Japanese industrial standard (JIS) method of JIS-M8812 and JIS-M8813.

2.2 Evaluation method of the combustion characteristics of the rice husk and straw

Combustion characteristics of rice husk and straw were analyzed by the thermogravimetric/differential thermal analysis (TG/DTA, Model DTG-60, Shimadzu Co. Ltd., Japan), and under the following conditions: samples were prepared below 250 μm by several sieves. About 4.0 mg of samples were heated at a rate of 5°C min^{-1} starting from room temperature until 900°C. A gas flow rate of 250 mL min^{-1} was used; clean gas was used as the carrier gas for combustion.

2.3 Evaluation of suspended particulate matter (SPM) in exhaust gases

2.3.1 Air sampling method for method for exhaust gases collection

Biomass burning is an important source of primary fine particles in the atmosphere, which can influence the regional air pollution and human health. Recently, fine particles below 2.5 μm in aerodynamic diameter (e.g. $PM_{2.5}$) either emitted from biomass burning or generated by photochemical reactions, are of great concern because of their effect on health and environment in Japan. For example, coarse particles of suspended particulate matter are mainly having particle sizes larger than 2 μm and are unable to instruction in to entering the respiratory tract by the nose, throat, and pharynges. Therefore, in this study, the $PM_{2.5}$ from combustion of waste rise husk and straw is evaluated. The collection devices of exhaust gases are shown in fig. 1. In order to evaluate the $PM_{2.5}$ emissions for the combustor, exhaust $PM_{2.5}$ were collected on quartz-fiber filters (35 mm φ, Pallflex Products Corp, 2500QAT-UP) and Teflon filters (35 mm φ, Pallflex Products Corp, T8711A) using two air samplers which are called the $PM_{2.5}$ personal sampler (Model NWPS-35HS, Sibata Scientific Technology Co. Ltd., Japan). The quartz-fiber filter was used for carbonaceous and ionic composition analysis, and the Teflon filters were used for metal composition analysis. Gaseous components (CO, CO_2, NOx and O_2) were also evaluated by portable gas analyzer (Model PG-250, Horiba Co. Ltd.).

2.3.2 Evaluation of carbonaceous compositions of $PM_{2.5}$ in exhaust gases

Carbonaceous analysis was based on the IMPROVE method (Interagency Monitoring of Protected Visual Environment) by the thermo-optical carbon analyzer (thermo/optical carbon analyzer: Model 2001, Desert Research Institute) shown in table 1. In this method, a 0.503 cm^2 (8 mm diameter) punch

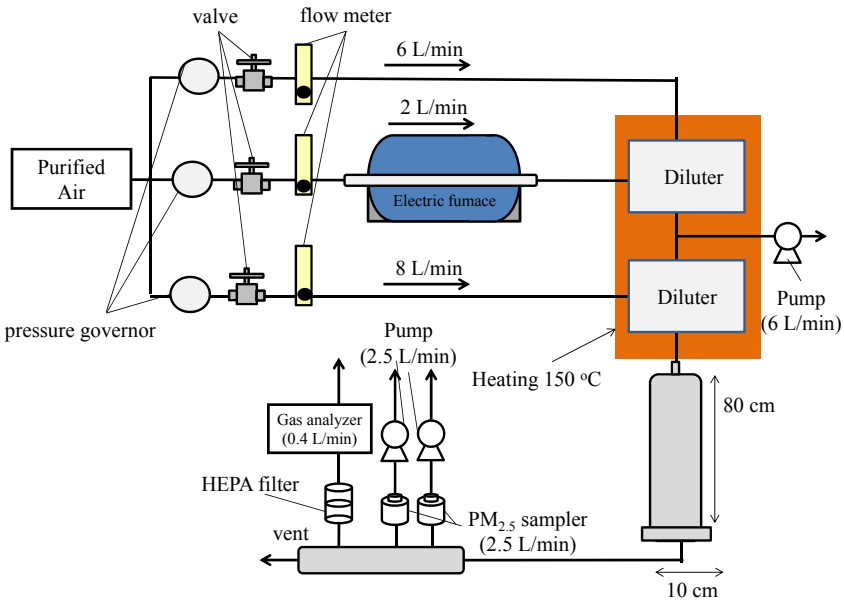

Figure 1: Air sampling setup for exhaust gases emitted from the combustor.

Table 1: Protocol of IMPROVE thermal/optical method for carbonaceous analysis.

Thermal/optical method		
Fraction	Temperature (°C)	Atmosphere
OC1	120	100% He
OC2	240	
OC3	450	
OC4	550	
EC1	550	2% O_2 + 98% He
EC2	700	
EC3	800	

aliquot of a sample quartz filter was heated at 120ºC (OC1), 250ºC (OC2), 450ºC (OC3), and 550ºC (OC4) in a helium atmosphere, and then at 550ºC (EC1), 700ºC (EC2), and 800ºC (EC3) in an oxidizing atmosphere of 2% oxygen and 98% helium. The analysis was repeated two or three times for each sample for better accuracy. $PM_{2.5}$ samples were collected at the flow rate of 2.5 L min^{-1} for the combustion out on each sampling with the $PM_{2.5}$ personal sampler.

2.3.3 Evaluation of ionic composition of suspended particulate matter in exhaust gases

One half of the 35 mm φ quartz-filter was ultrasonically extracted with 5 mL ultrapure water (18.2MΩ milli-Q ultrapure water) for 20 minutes, in order to carry the ionic composition analysis. The concentrations of the following cations were measured: Ca^{2+}, K^{+}, NH^{4+}, and Na^{+} and the following anions: SO_4^{2-}, NO^{3-}, and Cl^{-} anions and cations were analyzed in two different ion chromatographs (IC, Model DX-100, Dionex Co. Ltd., Japan).

3 Results and discussion

3.1 Measurements in the composition of waste rice husk and straw

The bulk composition of biomass in terms of carbon, hydrogen, and oxygen (CHO) did not differ much among different biomass sources. Typical dry weight percentages for C, H, and O were 30% to 60%, 5% to 6%, and 30% to 45% respectively [8]. Table 2 shows the composition analysis of waste rice husk and straw. As the results from the proximate analysis of rice husk indicated, ash contents were high in waste rice husk, while the carbon contents were low from the ultimate analysis of waste rice husk and straw. This means that waste rice husk heating value is lower than that of waste rice straw. However, waste rice husk and straw is much lower when compared to fossil fuel. Therefore, it is necessary to find the suitable combustion conditions for effective utilization as biomass fuel of waste rice husk and straw.

Table 2: Rice husk and straw composition analysis.

	Proximate analysis (wt%)				Ultimate analysis (wt%)			
Sample	M	VM	Ash	FC	C	H	N	O
Rice husk	5.4	62.5	17.5	14.6	45.11	5.87	0.52	30.99
Rice straw	5.3	69.2	9.2	16.3	39.19	5.26	0.51	45.89

M: Moisture, VM: Volatile matter and FC: Fixed carbon.

3.2 Differential combustion characteristics of the rice husk types

A similar trend was observed for rice husk and rice straw in the case of TG/DTA (figure 2). The TG/DTA thermogram for rice husk showed two well-defined peaks at 280°C and around 400°C. These results show that waste rice husk achieves its pyrolysis at around 280°C, where the more volatile components were burned while the carbonized fraction was burned at a higher temperature, around 400°C. For this reason, the waste rice husk can only be combusted under conditions at temperatures above 500°C. In this study, combustion was carried out at temperatures between 500 and 1000°C in increments of 100°C.

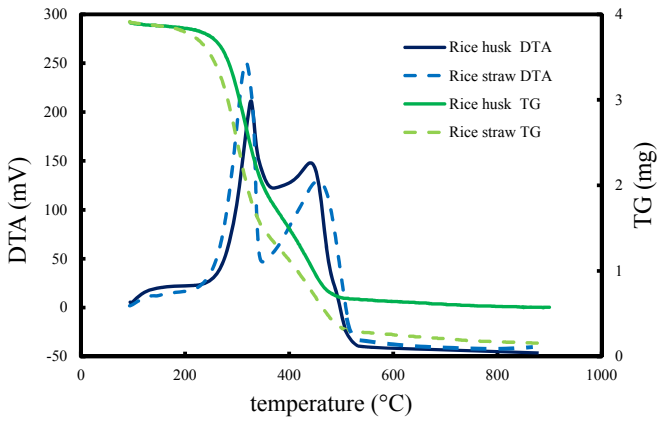

Figure 2: Pyrolysis and combustion behavior of rice husk and rice straw.

3.3 Air pollutant emitted from combustion of waste rice husk under different combustion temperatures

3.3.1 Gases components and combustion efficiencies

In this study, to simplify the combustion efficiency, account was taken of the fact that >90% of the carbon combusted in a fire was emitted in the form of CO_2 and CO, and <10% of carbon was in species such as hydrocarbons and particulate carbon. With this in mind, the modified combustion efficiency (MCE) can be defined as

$$\mathrm{MCE} = \frac{[C]_{CO_2}}{[C]_{CO} + [C]_{CO_2}} \tag{1}$$

The combustion conditions can be categorized according to the MCE: MCE ≧ 0.9 indicates smoldering combustion and MCE < 0.9 indicates flaming combustion [9].

The behavior of gaseous components during waste rice husk and straw combustion under different temperatures (500–1000°C) is shown in fig. 3. It was found that all of gas concentrations showed the similar behavior in two temperature ranges 500–700°C and 800–1000°C.

Figure 4 shows the variation of the modified combustion efficiency (MCE) under all combustion conditions with the different temperatures. For example, as fig. 3 also shows, within the temperature range 700–800°C, CO and O_2 concentrations were increased under smoldering combustion conditions and NO_X and CO_2 concentrations were increased under flaming combustion conditions. These results indicate that the combustion efficiencies under flaming combustion are better than under smoldering combustion. Biomass fuel is regarded as a renewable energy source with low CO_2 emissions if produced in a sustainable manner. From this point of view, if waste rice husk and straw is used as providing a more effective fuel combustion, the emission of CO_2 is less or not contributing to global warning.

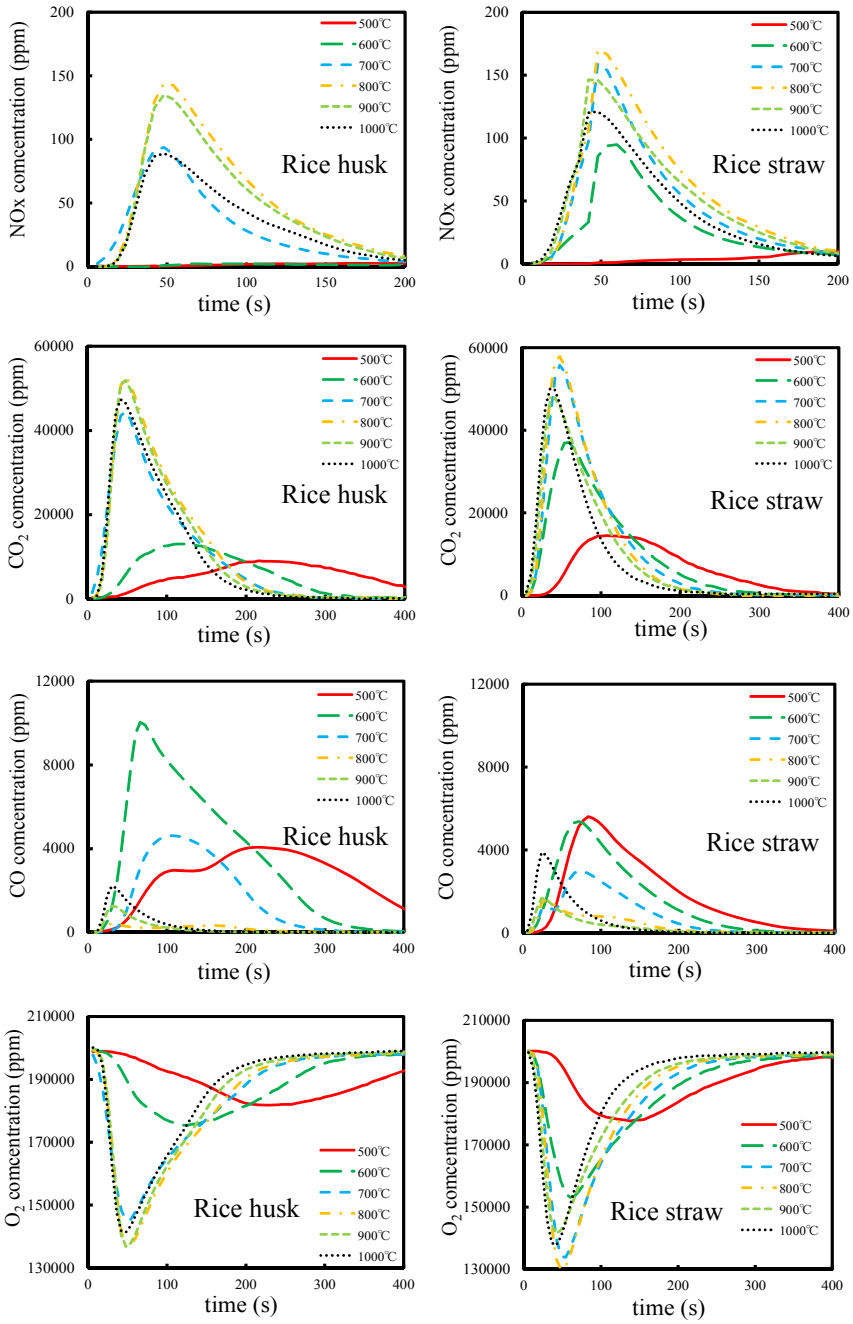

Figure 3: Gas components emitted from combustion of waste rice husk and straw under the different combustion temperatures.

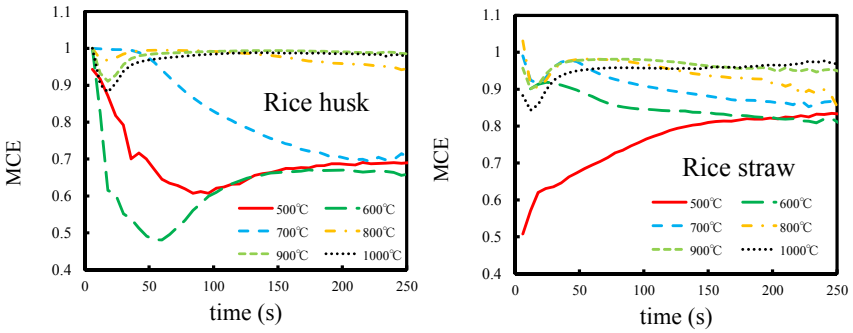

Figure 4: Gas components emitted from combustion of waste rice husk and straw under the different combustion temperatures.

3.3.2 Cabonaceous compositions in $PM_{2.5}$

The effect of combustion temperature on carbonaceous composition in $PM_{2.5}$ was investigated. The results of carbonaceous composition analysis are shown in fig. 5. OC compositions includes compounds like levoglucosan and methoxyphenol [10], which are generated in the thermolysis of cellulose and lignin; levoglucosan is one of the water-soluble organic substances and it can contribute to cloud condensation nuclei and influence the optical properties of aerosol. In our results, OC1 was found at the highest concentrations in smoldering combustion which is mainly generated by biomass combustion at low temperatures (500°C). On the other hand, in smoldering combustion, EC composition was dominated by EC1 (char-EC). Under flaming combustion, OC mass concentrations were decreased significantly, and EC concentrations were

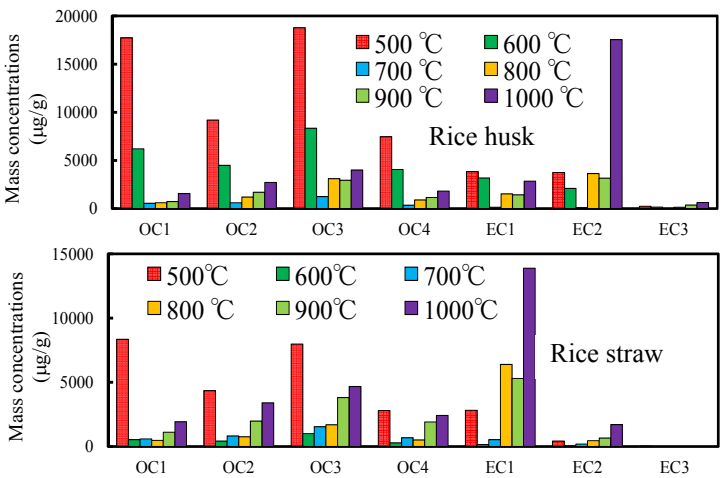

Figure 5: Carbonaceous components in $PM_{2.5}$ from combustion rice husk and straw at different combustion temperature.

dominated by EC2 (soot-EC). However, EC (EC1+EC2) were emitted by smoldering combustion. Here, EC is a mostly POC, POC is OC (OC3). Therefore, as shown in fig. 5, EC has not been nearly exhausted in smoldering combustion. From the results of total carbonaceous concentration (OC+EC), it is noted that the carbonaceous concentrations in $PM_{2.5}$ under flaming combustion were 10 times lower than under smoldering combustion.

3.3.3 Ionic compositions in $PM_{2.5}$

Ionic concentrations in $PM_{2.5}$ were almost unchanged by combustion temperature. The results are shown in fig. 6. The high concentrations of SO_4^{2-} in $PM_{2.5}$ were determined at all combustion temperatures. In general, K^+ is an important component of biomass [11], since it is used in metabolic processes; therefore, this component can be used as a marker for biomass combustion contributing to air pollution. However, in our results, K^+ concentrations were low at all combustion temperatures.

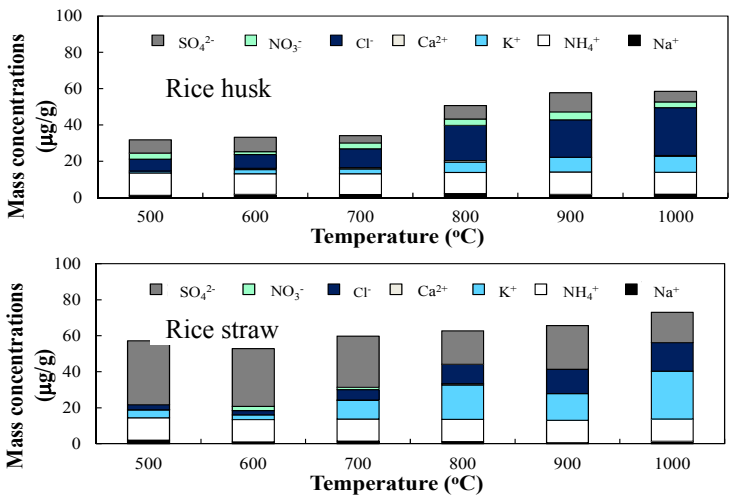

Figure 6: Ions components in $PM_{2.5}$ from combustion rice husk and straw at different combustion temperature.

As mentioned above, the behavior of harmful air pollutants emitted from rice husk and straw combustion were investigated by measuring carbonaceous and ionic composition of suspended particulate matter in $PM_{2.5}$ and the exhaust gases. It would be pleasing if this information is useful in production and application of small size combustors for waste rice husk or other biomass fuels. For further study, there is also need to analyze for polycyclic aromatic hydrocarbons (PAHs) emitted from rice husk and straw combustion in order to effectively reduce harmful air pollutants.

4 Conclusion

In this study, the possibility of waste rice husk and straw substitute fossil fuel was evaluated based on laboratory model combustion experiments. According to the combustion characteristics of rice husk and straw, it is possible to use as a biomass fuel if rice husk is combusted at the temperatures above 500°C. From analysis of gaseous compositions, it is indicated that flaming combustion (800–1000°C) proved better in its efficiency than smoldering combustion (500–700°C).

From the results of carbonaceous compositions, it was found that one tenth of carbonaceous particulate matter with smaller particle sizes may be only emitted under flaming combustion rather than under smoldering combustion. It can be suggested that air pollutants can be easily reduced if stable combustion performance under suitable conditions can be ensured especially for developing small size combustors.

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