JES

JOURNAL OF ENVIRONMENTAL SCIENCES

ISSN 1001-0742
CN 11-2629/X

March 1, 2013 Volume 25 Number 3
www.jesc.ac.cn

ELSEVIER
Science Press

Sponsored by
Research Center for Eco-Environmental Sciences
Chinese Academy of Sciences

ISSN 1001–0742 **Journal of Environmental Sciences** Vol. 25 No. 3 2013

CONTENTS

Serial parameter: CN 11-2629/X*1989*m*218*en*P*25*2013-3

Available online at www.sciencedirect.com

ScienceDirect

Journal of Environmental Sciences 2013, 25(3) 511–519

JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

Influence of fuel mass load, oxygen supply and burning rate on emission factor and size distribution of carbonaceous particulate matter from indoor corn straw burning

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Received 23 October 2012; revised 29 November 2012; accepted 03 December 2012

Abstract

The uncertainty in emission estimation is strongly associated with the variation in emission factor (EF), which could be influenced by a variety of factors such as fuel properties, stove type, fire management and even methods used in measurements. The impacts of these factors are complicated and often interact with each other. Controlled burning experiments were conducted to investigate the influences of fuel mass load, air supply and burning rate on the emissions and size distributions of carbonaceous particulate matter (PM) from indoor corn straw burning in a cooking stove. The results showed that the EFs of PM (EF_{PM}), organic carbon (EF_{OC}) and elemental carbon (EF_{EC}) were independent of the fuel mass load. The differences among them under different burning rates or air supply amounts were also found to be insignificant ($p > 0.05$) in the tested circumstances. PM from the indoor corn straw burning was dominated by fine PM with diameter less than 2.1 μm, contributing 86.4% ± 3.9% of the total. The size distribution of PM was influenced by the burning rate and air supply conditions. On average, EF_{PM}, EF_{OC} and EF_{EC} for corn straw burned in a residential cooking stove were (3.84 ± 1.02), (0.846 ± 0.895) and (0.391 ± 0.350) g/kg, respectively. EF_{PM}, EF_{OC} and EF_{EC} were found to be positively correlated with each other ($p < 0.05$), but they were not significantly correlated with the EF of co-emitted CO, suggesting that special attention should be paid to the use of CO as a surrogate for other incomplete combustion pollutants.

Key words: indoor corn straw burning; emission factor; size distribution; influencing factor

DOI: 10.1016/S1001-0742(12)60191-0

Introduction

Particulate matter (PM), especially fine PM, has been widely studied due to its adverse effect on air quality, human health and climate change. Increased ambient levels of fine PM are thought to be an important reason for the decrease of visibility in many cities (Che et al., 2007, 2009; Wang et al., 2012). Fine PM can penetrate deep into the lung area. Exposure to serious fine PM pollution is thought to be associated with increased risks of various respiratory and cardiovascular diseases and mortality rates (Brook et al., 2010; Dockery et al., 1993; Englert, 2004; Huang et al., 2012; Kan et al., 2012; Pope et al., 2009; Rich et al., 2012). In a two year follow-up of cardiovascular disease patients, Huang et al. (2012) reported a significant reduction in heart rate variability index associated with reduced exposure to air pollutants, especially fine $PM_{2.5}$ (PM with diameter less than 2.5 μm) and black carbon. Kan et al. (2012) reviewed epidemiological studies of ambient air pollution conducted in China so far, and pointed out that the increased mortality and morbidity risks (per amount of pollution) in the Chinese population were lower than those in developed countries; however, because of the much higher contamination, the importance of these risks was thought to be much greater. The mechanism of adverse health effects induced by PM exposure is not so clear at this stage. It is generally believed to be related to the reactive oxygen species from PM and associated with the physico-chemical properties of the PM, like particle size and its chemical compositions associated with high temporal and spatial variations. As a climate-relevant pollutant, it has been accepted in general that the sulfate and organic carbon (OC) content in PM usually have cooling effects

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by scattering light, while element carbon (EC) may have a positive radioactive forcing effect due to light absorption (Chow et al., 2011; Cheng et al., 2011; Jacobson, 2000).

To study the transport and fate behaviors of a pollutant, and analyze the environmental impacts and pollution control strategy, the development of an emission inventory of the pollutant is necessary. Emission estimation is usually based on the total fuel consumption and emission factors (EFs), defined as mass of the pollutant per mass of consumed fuel, or per unit energy (Bond et al., 2004; Zhang et al., 2000). An accurate estimation with high resolution at both regional and global scales is urgently needed (Cappa et al., 2012; Chow et al., 2011; Chung et al., 2012). However, current emission estimations in the literature generally have relatively high uncertainties and bias because of the limited data available and the high degree of variation, especially in EFs (Bond et al., 2004; Cao et al., 2008; Cappa et al., 2012; Chow et al., 2011; Chung et al., 2012; Li et al., 2007, 2009; Yan et al., 2006). EFs for a target can be measured directly or derived from EFs of another surrogate based on their quantitative relationship. EFs reported in the literature often vary dramatically due to the difference in fuel properties (e.g. bulk density and moisture), stove types (e.g. traditional or improved stoves with or without a chimney), burning conditions (e.g. oxygen supply amount, fuel/air mixing status and fire management pattern), and even experimental methods (e.g. laboratory chamber study, simulated combustion or field measurement) (Bignal et al., 2008; Chen et al., 2012; Dhammapala et al., 2006, 2007; Lee et al., 2005; Roden et al., 2006, 2009; McDonald et al., 2000; Jetter et al., 2012). For example, emissions of organic compounds from prescribed burning were much higher than those from combustion in fireplaces and laboratory-simulated burning (Lee et al., 2005). It was reported that EFs of PM from residential wood combustion in cooking stoves were about 2–4 times higher in field measurements in comparison to those in laboratory investigations (Roden et al., 2006, 2009). But a good comparison between field measurements and laboratory studies was also found when taking the combustion efficiency into consideration (Christian et al., 2003; Dhammapala et al., 2007). EFs were generally lower from combustion at higher combustion efficiencies. The combustion efficiency could be influenced by various factors including fuel moisture, oxygen supply amounts and fuel/air mixing status, and even fire management (Dhammapala et al., 2007; McMeeking et al., 2009; Janhäll et al., 2010). It has been accepted that the impacts of fuel properties and burning conditions are complicated and sometimes interact with each other (Lu et al., 2009; Rogge et al., 1998; Simoneit, 2002).

Field measurements are able to get representative and reliable EFs, but also require relatively high labor intensity and cost, and are usually time-consuming. Laboratory simulation studies are commonly conducted to model the combustion process providing information and also enough samples for emission characterization, and to obtain EFs for various pollutants from different burning conditions in a relatively short study period. The latter also provide the opportunity to investigate the influence of fuel properties and burning conditions under controlled conditions (Grandesso et al., 2011; Lu et al., 2009; Ryu et al., 2006; Xie et al., 2009). For example, Ryu et al. (2006) investigated the influence of fuel bulk density, size and air flow rate on emissions from biomass combustion in a fixed bed. Grandesso et al. (2011) simulated open biomass burning in the laboratory and studied the effect of moisture (7%–50%) and fuel charge size (1–10 kg) on polychlorinated dibenzo-*p*-dioxin and dibenzofuran (PCDD/F) emissions, and found that the total EFs of PCDD/F and toxic equivalency were not significantly influenced by fuel charge size and moisture. Xie et al. (2007) studied the influence of excess air, the degree of air staging and the fuel feeding position on the emissions of gaseous SO_2 and NO_x from the burning of coal in a bench-scale circulating fluidized bed combustor. Lu et al. (2009) investigated the influence of combustion temperature, fuel moisture and oxygen amount on polycyclic aromatic hydrocarbon emissions from crop straw burning in a laboratory chamber under controlled conditions.

Residential biomass burning is a large emitter of fine PM, OC and EC in China (Bond et al., 2004; Lei et al., 2011; Wang et al., 2012). It was estimated that the total emissions of $PM_{2.5}$, PM_{10} (PM with diameter less than 10 μm), total suspended particles (TSP), OC and EC in China were 13.0, 18.8, 34.3, 3.19 and 1.51 Tg in 2005, of which 27.7%, 19.8%, 11.3%, 71.8% and 39.1% were from indoor biomass burning (Lei et al., 2011). In our previous study, the EFs of PM, OC and EC from indoor crop straw burning were measured in a rural kitchen. Nine types of crop straw were burned, and the influences of fuel moisture and combustion efficiency on measured EFs were quantitatively analyzed (Shen et al., 2010). The main objective of the present study is to investigate the influence of fuel mass load, burning rate and air supply conditions on the emission of carbonaceous PM from indoor corn straw burning in a residential cooking stove. The burning processes were conducted in a real cooking stove in a rural kitchen, rather than a laboratory chamber. In addition to the total emissions of PM, the size distributions of PM under different circumstances were also characterized.

1 Materials and methods

1.1 Combustion experiment

Combustion experiments were conducted in a rural kitchen. The kitchen was built previously to measure the emission factors of pollutants from residential solid fuel combustion in rural Northern China (Shen et al., 2010, 2012). A commonly used brick cooking stove (80 cm in length, 70 cm in width and 65 cm in height) with one iron pot in the middle was used. The combustion chamber was approximately 0.20 m^3, and the grate air inlet area was 0.09 m^2. Corn, rice and wheat are three main crops grown in China, and the straw of corn, rice and wheat contribute about 40%, 18% and 20% of the total crop residue combusted in rural areas (Cao et al., 2008; Zeng et al., 2007). In this study, corn straw with moisture of 7.02% was burned. More detailed information of the stove and corn straw properties can be found elsewhere (Shen et al., 2010).

To investigate the influence of fuel mass load on the emissions of carbonaceous PM, three different load conditions with fuel mass at 275, 550, and 1100 g, respectively, were adopted. Corn straw was inserted into the combustion stove in several batches following the routine pattern used by the rural residents in their daily lives. The calculated fuel burning rate in the combustion of 550 g corn straw in the routine practice was (0.045 ± 0.002) kg/min. To assess the influence of fuel burning rate, increased and reduced fuel burning rates were achieved by burning a total of 550 g corn straw in two different batch numbers, which meant a change of fuel mass added in one batch. In the faster burning trial with more fuel added per batch, the burning lasted a shorter time with calculated burning rate of (0.119 ± 0.016) kg/min, and the burning rate was only (0.020 ± 0.001) kg/min when the corn straw burning lasted longer in the man-made slow burning experiment. The air supply rate in the routine corn straw burning with only natural ventilation in the present study was estimated at to be about 9.0 m^3/hr (Wei, 2012). To investigate the potential influence of air supply on emission performance, two additional combustion experiments with reduced and enhanced air supply were conducted. One additional blower was used to get a higher ventilation rate (ca. 19.0 m^3/hr) during the corn straw burning. A lower air supply amount during the burning was achieved by decreasing the grate air inlet area to 0.04 m^2. **Figure 1** shows the experimental design of the present study. In all circumstances, combustion experiments were done in triplicate.

1.2 Sampling and measurement

The exhaust from the combustion entered into a mixing chamber (4.5 m^3) with a small fan built-in. The sampling port was placed in the center of the mixing chamber, and no further dilution was conducted to avoid potential impacts of dilution ratio and rate on the mass and size distribution of particles emitted (Roden et al., 2006; Shen et al., 2010). PM was collected on quartz fiber filters using a low-volume pump (XQC-15E, Tianyue, China) at a flow rate of 1.5 L/min. In addition to total PM, size-segregated samples were collected using a nine stage cascade impactor (FA-3, Kangjie, China) with cutoff diameters at < 0.4, 0.4–0.7, 0.7–1.1, 1.1–2.1, 2.1–3.3, 3.3–4.7, 4.7–5.8, 5.8–9.0, and 9.0–10.0 μm at a flow rate of 28.3 L/min.

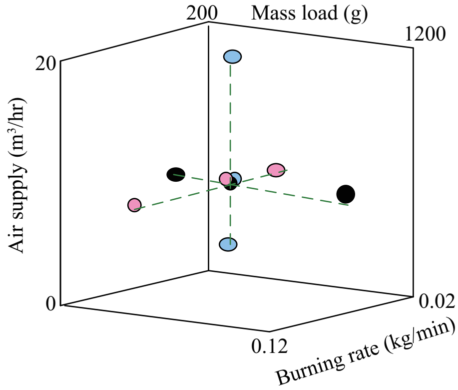

Fig. 1 Experimental design (different fuel mass load, air supply condition and burning rate) of each test circumstance in the present study. For each scenario, triplicate combustion experiments were conducted.

After sampling, particle-loaded filters were wrapped with pre-baked aluminum foil and stored in a desiccator for 24 hr prior to weighing. A high-precision digital balance (0.00001 g) was used in the PM gravimetric measurements. EC and OC compositions in PM were determined with a Sunset EC/OC analyzer using thermal-optical transmission (Sunset Lab, USA). The temperature protocol was 600, 840, and 550°C in a pure helium atmosphere for OC, and then at 550, 650, and 870°C in an oxygen/helium atmosphere for EC detection. Pyrolyzed organic carbon was determined when the laser signal returned to the initial value and subtracted from EC. CO_2 and CO were measured and recorded automatically every 2 sec with an on-line detector equipped with a non-dispersive infrared sensor (GXH-3051, Technical Institute, China). The equipment was calibrated using a span gas before each experiment and zero checked afterward. All filters used were pre-baked at 450°C for 6 hr and equilibrated in a desiccator. Blank samples were also collected and the results were subtracted.

1.3 Data analysis

The emission factors of PM, OC, and EC (EF_{PM}, EF_{OC} and EF_{EC}, respectively) were determined based on the carbon mass balance method (Zhang et al., 2000). It was assumed that total carbon burned was released in the forms of gaseous CO, CO_2, total gaseous hydrocarbons and carbon in PM. In the present study, total gaseous hydrocarbons was not measured since most of the gaseous carbon was emitted in the forms of CO or CO_2, and the neglect may result in an error less than 4% (Roden et al., 2006). It was reported that EFs calculated using the carbon mass balance method were comparable to those from direct measurements (Dhammapale et al., 2006). Since it is not necessary to collect all the emitted species and the site of sampling port is flexible in the flue gas, the carbon method has been widely used in EF measurements (Dhammapale et al., 2006, 2007; Roden et al., 2006, 2009; Zhang et al., 2000). The detailed description of the EF calculation can be found elsewhere (Zhang et al., 2000; Shen et al., 2010).

The combustion efficiency is usually defined as the mass of carbon emitted in the form of CO_2 divided by the total amount of carbon released. Since most of the carbon was released in the forms of CO or CO_2, the modified combustion efficiency (MCE), defined as CO/(CO_2+CO) ratio (molar basis), has also been commonly calculated and used to describe the combustion condition (Dhammapala et al., 2006; Janhäll et al., 2010). In the present study, the MCE was calculated. Non-parametric analysis was applied for data analysis using Statistica at a significant level of 0.05.

2 Results and discussion

2.1 Influence of fuel mass load

The MCEs of the corn straw burning with mass load at 275, 550, and 1100 g were 95.4% ± 0.2%, 96.1% ± 0.4% and 96.8% ± 0.3%, respectively (p > 0.05). Measured EF_{PM}s in these three burning circumstances were (3.29 ± 0.11), (4.65 ± 0.07), and (3.68 ± 0.55) g/kg, respectively. There were no significant differences among these EF_{PM} (p > 0.05). Insignificant differences were also found in measured EF_{OC} and EF_{EC} values (p > 0.05). Means and standard derivations for EF_{OC} from the burning of 275, 550, and 1100 g corn straw were (0.635 ± 0.257), (0.879 ± 0.367), (0.495 ± 0.322) g/kg, and were (0.149 ± 0.048), (0.401 ± 0.029), (0.905 ± 0.655) g/kg for EF_{EC}, respectively. The ratio of OC and EC, and the total carbon mass fraction in PM (TC/PM, and TC = EC + OC) are two useful parameters in the study of carbonaceous particulate matter, and are commonly used in source apportionment and climate effect analysis (Bond et al., 2004; Zhi et al., 2009). The calculated OC/TC and TC/PM ratios were also independent of the burned fuel mass load. On average, the OC/TC ratio was 0.60 ± 0.20, and total carbon contributed about 29.0% of the PM mass.

Figure 2 shows the size distribution of PM emitted from corn straw burning under different fuel mass loads. Generally, fine particles dominated the total PM emission from the indoor corn straw burning. Under low, medium and high fuel mass load conditions in the present study, the mass fractions of $PM_{2.1}$ (PM with diameter less than 2.1 μm, the closest to $PM_{2.5}$ in this study) were 85.9% ± 2.0%, 87.9% ± 1.1% and 87.0% ± 1.5% of the total, respectively. $PM_{1.1}$ (PM with diameter less than 1.1 μm, the closest to $PM_{1.0}$) made up 77.2% ± 3.2%, 77.9% ± 2.8% and 67.7% ± 1.6%, respectively. There were no significant differences among the PM size distributions from the burning of corn straw with different fuel mass load (p > 0.05).

It was reported previously that when the fuel mass load increased from 1 to 10 kg, the measured PM concentrations from simulated open biomass burning did not vary significantly (Grandesso et al., 2011). Given the lack of any significant change tendencies observed for EF_{PM}, EF_{OC} and EF_{EC} with different fuel mass loads observed in this study, it was suggested that the effect of mass load on the measured EF data was limited. In a field study on the emission and ambient pollution levels of carbonaceous PM from indoor biomass burning in a rural household in Northern China, the consumption of corn straw was documented at about 0.3–0.8 kg/(person·day) (Ding et al., 2012; Zhong et al., 2012).

2.2 Influence of burning rate

In the corn straw burning at relatively slow (0.020 ± 0.001 kg/min), medium (0.045 ± 0.002 kg/min) and fast rates (0.119 ± 0.016 kg/min), MCEs were 96.2% ± 0.1%, 96.1% ± 0.4 % and 95.2% ± 0.6%, respectively, decreasing with the increase of fuel burning rate in general (p > 0.05). The measured EF_{PM}, EF_{OC} and EF_{EC} results in the slow burning were (4.54 ± 1.17), (0.636 ± 0.664) and (0.215 ± 0.304) g/kg, respectively. In the fast burning, EF_{PM}, EF_{OC} and EF_{EC} were (3.57 ± 0.82), (0.338 ± 0.338) and (0.342 ± 0.294) g/kg, respectively. The results were not significantly different from those in corn straw burning at the medium rate (p > 0.05). The ratios of OC/TC and TC/PM were also not significantly different among

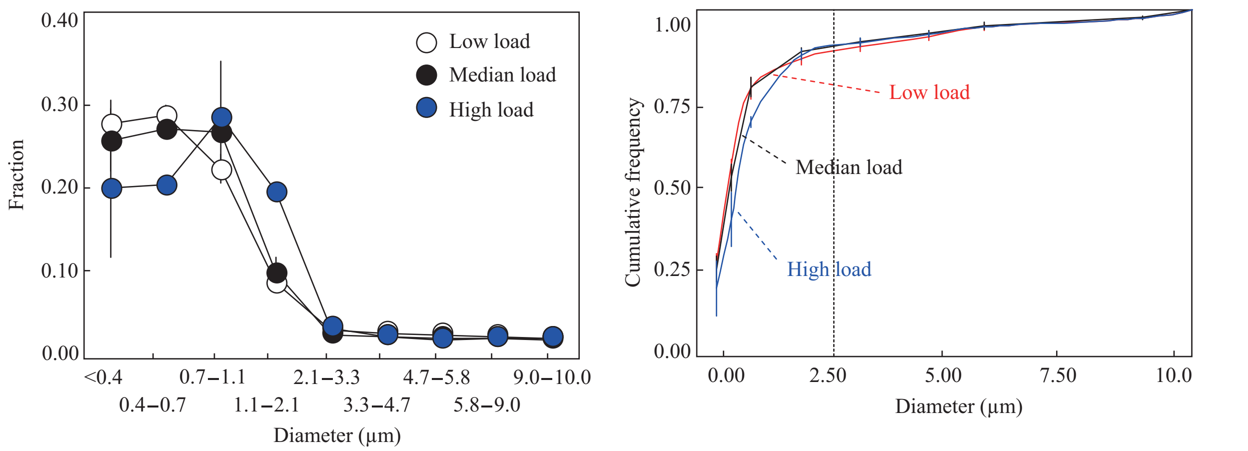

Fig. 2 Size distribution of PM from indoor corn straw combustion at different mass loads. Results shown are means and standard derivations of triplicate measurements.

the experiments with these three burning rate levels. It was thought that burning too fast could cause an oxygen-limited condition that would produce high emissions of various pollutants from incomplete combustion (Jenkins et al., 1996; Simoneit, 2002; McDonald et al., 2000; Rogge et al., 1998). However, relatively large variations in measurements were found to result in statistically insignificant differences in measured EFs under different burning rates.

Size distributions of the PM emitted from corn straw burning under different burning rates are compared in **Fig. 3**. $PM_{1.1}$ and $PM_{2.1}$ fractions were 84.8% ± 1.0% and 91.5% ± 0.9% of the total in the slow burning, were 77.9% ± 2.8% and 87.9% ± 1.1% in corn straw burning at the medium burning rate, and were 53.2% ± 6.1% and 85.0% ± 1.0% of the total PM in the fast burning experiment. The contribution of fine particles generally declined with the increase of fuel burning rates. The phenomena could be partly explained by the oxygen deficient condition formed at a fast burning rate. It was reported that high oxygen could sustain the intense flaming conditions that benefit the emissions of fine particles from biomass burning (Hays et al., 2003). As a result, the formation and emission of fine particles would decrease when fuels burned too fast and an oxygen-deficient atmosphere was formed in the combustion chamber (Simoneit, 2002; Rogge et al., 1998).

The fuel burning rate in the field was mainly determined by the fire care and skill of the residents during the burning process. In rural residents' daily lives, the fuel burning rate measured in a previous field study was in the range of 0.029 to 0.064 kg/min (Ding et al., 2012). The rate fell into the range of the slow and medium burning rates in the present study. As mentioned, a fast burning could produce high emissions of incomplete pollutants because of the oxygen-deficient atmosphere formed. However, it was also suggested from this study that under these relatively low burning rates, the yield of fine PM might be higher though the emission of total particles did not change significantly in comparison with the emission from the fast burning.

2.3 Influence of air supply

It is accepted that adequate air supply is required for stable and highly efficient combustion with low emission of incomplete combustion pollutants (Houshfar et al., 2011; Lu et al., 2009; Ryu et al., 2006; Xie et al., 2007). Fuel combustion in oxygen-deficient conditions usually produced high emissions of pollutants from incomplete combustion (Jenkins et al., 1996; Zhang et al., 2008), while increased air supply may cool down the combustion temperature and result in the increased emissions of the incomplete combustion pollutants (Johansson et al., 2003; Skreiberg et al., 1997; Houshfar et al., 2011). Excess air ratio, defined as the ratio of actual air quantity to theoretical air requirement, has been commonly used to quantitatively describe the air supply condition during the combustion process (Liu et al., 2001; Venkataraman et al., 2004). It was suggested that the optimized excess air ratio should be around 2.0 (Liu et al., 2001). In the present study, calculated excess air ratios in three burning experiments with reduced (ca. 4.0 m^3/hr), medium (ca. 9.0 m^3/hr, a routine situation in rural household biomass burning practice) and enhanced (ca. 19 m^3/hr) air supply rates were (1.40 ± 0.04), (2.44 ± 0.09) and (4.52 ± 0.18), respectively.

MCEs for the tested corn straw burning with the low and high air supply rates were 92.7% ± 0.7% and (95.2% ± 1.1)%, respectively, which were lower (p < 0.05) than 96.1% ± 0.4% in normal burning conditions with medium air supply. The measured EF_{PM}, EF_{OC} and EF_{EC} from the combustion with reduced air supply were (3.83 ± 1.04), (2.16 ± 1.88) and (0.277 ± 0.138) g/kg, and were (3.29 ± 2.04), (0.769 ± 0.543) and (0.319 ± 0.224) g/kg in the burning with a high air supply, respectively. The results were not significantly different (p > 0.05) from those from the burning in the normal situation with medium air supply (EF_{PM}, EF_{OC} and EF_{EC} at (4.65 ± 0.07), (0.879 ± 0.367) and (0.401 ± 0.029) g/kg, respectively), mainly due to large variations in the measurements. Also, the

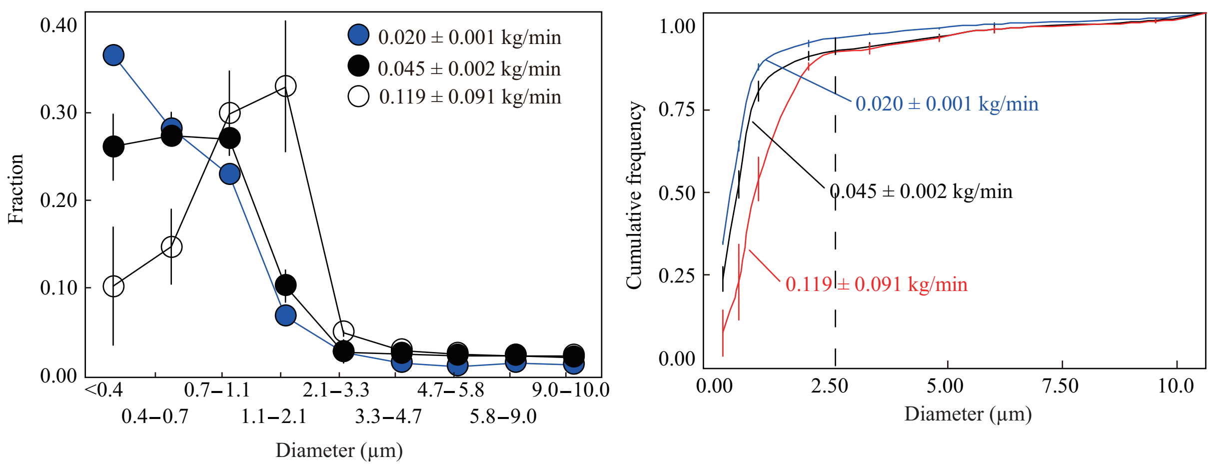

Fig. 3 Size distribution of PM from indoor corn straw burning under different burning rates. Results shown are means and standard derivations of triplicate measurements.

ratios of OC/TC and TC/PM were comparable in burning experiments under different air supply conditions.

In PM emission, $PM_{2.1}$ contributed 88.5% ± 3.5%, 87.9% ± 1.1% and 78.9% ± 1.7% of the total in the burning with low, medium and high air supply rates, and the mass fractions of $PM_{1.1}$ were 53.0% ± 17.4%, 77.9% ± 2.8% and 55.3% ± 10.2% of the total in these three burning circumstances, respectively ($p > 0.05$). **Figure 4** compares the size distributions of PM from the corn straw burning under different air supply conditions. A slight difference was found in the PM size distribution. In the burning under routine air supply conditions, the distribution was dominated by fine PM with diameter between 0.4 and 0.7 μm ($PM_{0.4-0.7}$) and between 0.7 and 1.1 μm ($PM_{0.7-1.1}$), followed by those with diameter less than 0.4 μm ($PM_{0.4}$). But in the burning trials with either reduced or enhanced air supply, the most abundant PM fractions were $PM_{1.1-2.1}$ and $PM_{0.7-1.1}$ followed by $PM_{0.4-0.7}$ and $PM_{0.4}$. Oxygen-deficient conditions formed in the combustion chamber with small air supply amounts were responsible for the decreased mass fractions of fine $PM_{0.4}$ and $PM_{0.4-0.7}$, since fine particles were preferably formed in intense flaming conditions that could be sustained by adequate oxygen supply (Hays et al., 2003). In the burning with a high air supply amount, the decrease in mass fractions of these fine $PM_{0.4}$ and $PM_{0.4-0.7}$ might be partly explained by the cooled combustion temperature that was not favorable for the formation of fine particles (Purvis et al., 2000; Shen et al., 2010; Venkataraman et al., 2004). It seems that the non-linear impacts of air supply not only exist in emission factors, but also on the PM size distribution. The influence is complicated and the mechanism is not very clear at this stage, especially its influence on PM size distribution (Hedberg et al., 2002; Wardoyo et al., 2007). Further study on the influences of air supply on both PM EF and size distribution is required.

2.4 Relationship among co-emitted pollutants

EF_{PM} was positively correlated with EF_{OC} ($r = 0.446$, $p = 0.021$) and EF_{EC} ($r = 0.480$, $p = 0.014$). The relationship between EF_{OC} and EF_{EC} was also significantly positive ($r = 0.481$, $p = 0.014$). Similar results were reported in the previous study (Shen et al., 2010, 2012). As mentioned above, the impacts of investigated factors, significant or not, were similar on EF_{PM}, EF_{OC} and EF_{EC}. The ratios of OC/TC and TC/PM did not show significant differences in the distinct burning circumstances. Taking all data in this study into consideration, the ratio of OC/TC was 0.67 ± 0.19, and the total carbon mass percent in PM was approximate 27.3%.

It is also interesting to investigate the relationship between carbonaceous particulate matter and CO, which is an important byproduct of incomplete combustion. As incomplete combustion pollutants are often emitted simultaneously from the burning process, a positive correlation between EF_{PM} and EF_{CO} has been reported in the literature (Bignal et al., 2008; Gupta et al., 1998; Jetter et al., 2012; Venkataraman and Rao, 2001). However, a converse tendency showing decreased PM emission with increasing CO emission was also observed in residential biomass burning (Li et al., 2007; Venkataraman et al., 2004). In the present study, there were no significant correlations found between EF of CO (EF_{CO}) and EF_{PM} ($p = 0.378$), between EF_{CO} and EF_{OC} ($p = 0.122$), and between EF_{CO} and EF_{EC} ($p = 0.206$), as shown in **Fig. 5**. A similar lack of relationship was also reported in the literature (Roden et al., 2009; Shen et al., 2012). The complicated relationship between CO and other co-emitted pollutants indicated that the use of CO as a surrogate for other incomplete combustion pollutants in the development of emission factors and emission inventory should be used with caution (Ballard-Tremeer and Jawurek, 1996; Venkataraman et al., 2004).

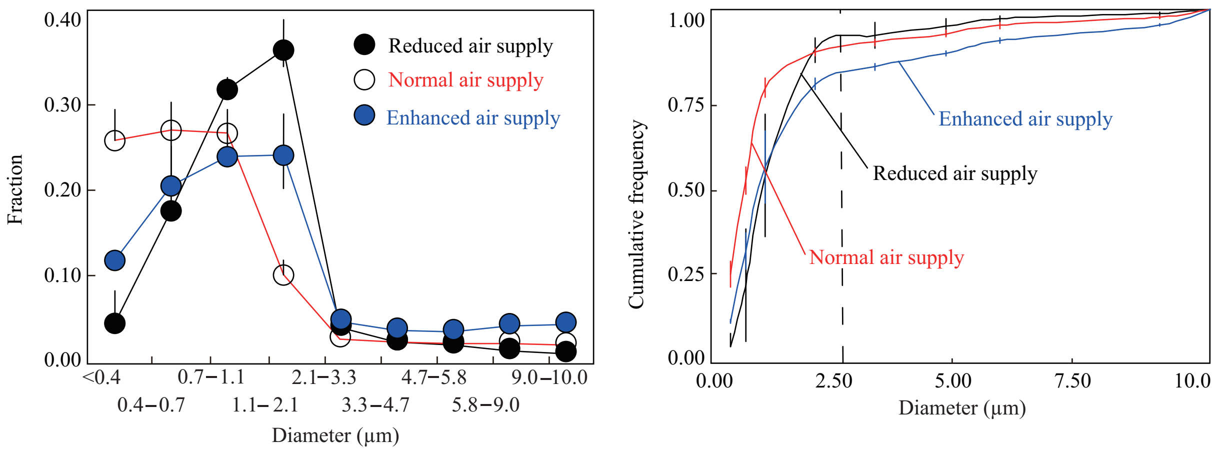

Fig. 4 Size distribution of PM from indoor corn straw burning for different oxygen supply. Data shown are means and standard derivations of triplicate measurements.

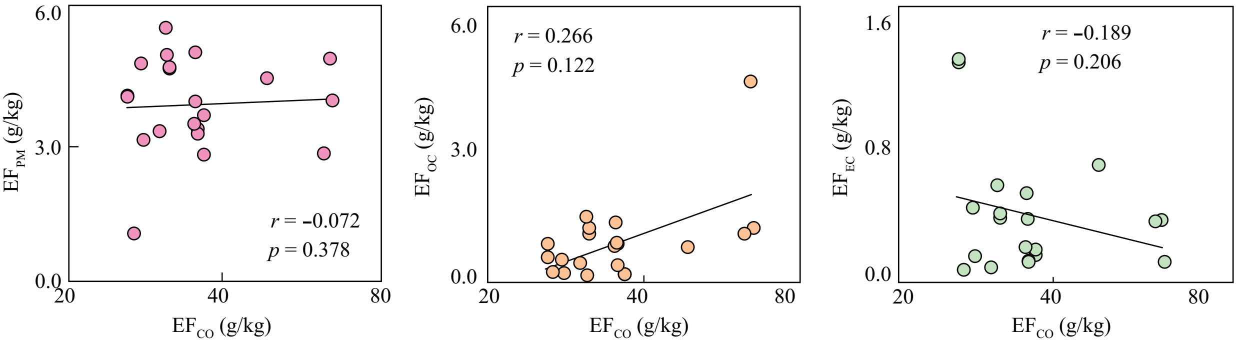

Fig. 5 Relationship between EF of CO and EFs of PM, OC, and EC from indoor corn straw burning. Data shown are results from all combustion experiments under different burning conditions.

3 Conclusions

The effects of fuel mass load, burning rate and air supply conditions on the emission and size distribution of carbonaceous particulate matter from indoor corn straw burning were evaluated. Measured EF_{PM}, EF_{OC} and EF_{EC} were in the range of 1.02–5.50, 0.129–4.34 and 0.073–1.29 g/kg with means and standard deviations of (4.65 ± 0.07), (0.879 ± 0.367) and (0.401 ± 0.029) g/kg, respectively, in normal burning conditions with fuel mass load of 0.55 kg. They were independent of fuel mass load. The impacts of burning rate and air supply amount were also found to be insignificant under the given circumstances, though fast burning or burning with a low air supply amount could result in an oxygen-deficient atmosphere, and increased air supply may cool the combustion temperature, both of which could lead to changes in the formation and emission of carbonaceous particulate matter. The relatively high variation in the measurements could be partly responsible for the insignificant differences found in this study. The EFs of PM, OC and EC were positively correlated with each other, but not significantly correlated with co-emitted CO.

Generally, PM from indoor corn straw burning was dominated by fine PM. $PM_{2.1}$ and $PM_{1.1}$ made up 86.4% ± 3.9% (77.7%–92.1%) and 67.0% ± 14.1% (40.7%–85.4%) of the total, respectively. The size distribution of PM could be also influenced by the burning conditions, like burning rate and air supply amounts. However, the reasons for these effects are not currently very clear. Future study on the influencing factors of PM with different sizes is of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 41130754, 41001343, 41001343), the Beijing Municipal Government (No. YB20101000101), the Ministry of Environmental Protection (No. 201209018) and NIEHS (No. P42 ES016465). Part of Guofeng Shen's work in Jiangsu Academy of Environmental Sciences was supported by the Environmental Protection Department of Jiangsu Province (Project: Status and Formation Mechanism of Combined Atmospheric Pollution in Nanjing and Surrounding Area). The authors also thank the reviewers for their valuable comments, and Dr. Rice for polishing the language.

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Journal of Environmental Sciences (Established in 1989)
Vol. 25 No. 3 2013

Supervised by	Chinese Academy of Sciences	**Published by**	Science Press, Beijing, China
Sponsored by	Research Center for Eco-Environmental		Elsevier Limited, The Netherlands
	Sciences, Chinese Academy of Sciences	**Distributed by**	
Edited by	Editorial Office of Journal of	Domestic	Science Press, 16 Donghuangchenggen
	Environmental Sciences		North Street, Beijing 100717, China
	P. O. Box 2871, Beijing 100085, China		Local Post Offices through China
	Tel: 86-10-62920553; http://www.jesc.ac.cn	Foreign	Elsevier Limited
	E-mail: jesc@263.net, jesc@rcees.ac.cn		http://www.elsevier.com/locate/jes
Editor-in-chief	Hongxiao Tang	**Printed by**	Beijing Beilin Printing House, 100083, China

CN 11-2629/X **Domestic postcode: 2-580** **Domestic price per issue RMB ¥ 110.00**

ISSN 1001-0742