Published in final edited form as:

J Environ Sci (China). 2013 March 1; 25(3): 511–519.

The 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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Abstract

The uncertainty in emission estimation is strongly associated with the variation in emission factor which could be influenced by a variety of factors, like fuel property, stove type, fire management and even methods used in measurements. The impacts of these factors were usually complicated and often interacted with each other. In the present study, controlled burning experiments were conducted to investigate the influence of fuel mass load, air supply and burning rate on the emission of carbonaceous particulate matter (PM) from indoor corn straw burning. Their impacts on PM size distribution were also studied. The results showed that EFs of PM (EF_{PM}), organic carbon (EF_{OC}) and element carbon (EF_{EC}) was 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, and PM with diameter less than $2.1 \mu m$ contributed about $86.4 \pm 3.9\%$ of the total. The size distribution of PM was also influenced by the burning rate and changed 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, but they were not significantly correlated with EF of co-emitted CO, suggesting a special attention should be paid to the use of CO acting as a surrogate for other incomplete pollutants.

Keywords

indoor corn straw burning; emission factor; size distribution; influencing factor

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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 were 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 was thought to be associated with the 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 III, *et al.*, 2009; Rich *et al.*, 2012). Though the mechanism of adverse health effects induced by PM exposure was not so clear at this stage, it was thought to be related to the physic-chemical properties of the PM, like particle size and its chemical compositions, and there are often high temporal and spatial variations existing. As a climate-relevant pollutant, it was generally believed that sulfate and organic carbon (OC) contents in PM usually have a cooling effect by scattering the light, while element carbon (EC) may have a positive radiative forcing because of light absorption (Chow *et al.*, 2011; Cheng *et al.*, 2011; Jacobson, 2000).

To study the transport and fate behaviors of a pollutant, and to analyze the environmental impacts and pollution control strategy, it is necessary to develop the emission inventory of the pollutant. An accurate estimation with a high resolution in 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 a high uncertainty and bias because of limited data available and 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). 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). EFs for a target can be measured directly or derived from EFs of another surrogate and their 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 a chimney or not), 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 the combustion in fireplace 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 good comparison between field measurements and laboratory studies was also found in some studies when taking the combustion efficiency into the consideration (Christian *et al.*, 2003; Dhammapala *et al.*, 2007). EFs were generally lower from the combustion in 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

was accepted that the impacts of fuel property and burning conditions were complicated and sometimes interacted with each other (Lu *et al.*, 2009; Rogge *et al.*, 1998; Simoneit, 2002).

While field measurements were able to get representative and reliable EFs, laboratory simulation studies were also commonly conducted to repeat the combustion process providing information and also enough samples for emission characterization studies, and to get EFs for various pollutants from different burning scenarios in a relatively short study period. The latter also provided 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 the open biomass burning in laboratory and studied the effect of moisture (7-50%) and fuel charge size (1-10 kg) on 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 (Grandesso *et al.*, 2011). 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 SO₂ 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 larger 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 with diameter less than 2.5 µm), PM₁₀ (PM with diameter less than 10 µm), total suspended particle (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, 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, size distributions of PM in different circumstances were also characterized.

1. Material 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 m³, and the grate air inlet area was 0.09 m². Corn, rice and wheat were three main crops grown in China, and the straw of corn, rice and wheat contributed about 40, 18 and 20% of the total crop residue

combusted in rural area (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 used 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 particulate matter, three different load conditions with fuel mass at 275, 550, and 1100 g, respectively were adopted. Fuels were inserted into the combustion chamber and burned following the routine pattern used by the rural residents in daily lives. To investigate the impact of fuel burning rate, one man-induced slower and another faster burning experiment were done in addition to the combustion conducted in a normal way with a median burning rate. Fuel mass loads in these three burning scenarios were all 550 g. Calculated burning rates were 0.020 ± 0.001 , 0.045 ± 0.002 and 0.119 ± 0.016 kg/min, respectively. Air supply rate in the routine corn straw burning with only natural ventilation in the present study was estimated at about $9.0 \text{ m}^3/\text{h}$ (Wei, 2012). To investigate the potential influence of air supply on emission performance, another two combustion scenarios with reduced and enhanced air supply were conducted. To get a higher ventilation rate ($\sim 19.0 \text{ m}^3/\text{h}$) during the corn straw burning, one additional blower was used. A lower air supply amount during the burning was achieved by decreasing the grate air inlet area to about 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 $1.5 \text{ L}/\text{min}$. In addition to total PM, size segregated samples were collected using a nine stage cascade impactor (FA-3, Kangjie, China) with the cutoff diameter at < 0.4 , $0.4\text{--}0.7$, $0.7\text{--}1.1$, $1.1\text{--}2.1$, $2.1\text{--}3.3$, $3.3\text{--}4.7$, $4.7\text{--}5.8$, $5.8\text{--}9.0$, and $9.0\text{--}10.0 \text{ }\mu\text{m}$ at a flow rate of $28.3 \text{ L}/\text{min}$.

After sampling, particle-loaded filters were packed with pre-baked aluminum foil and stored in a desiccator for 24 hours prior to weighing. A high precision digital balance (0.00001 g) was used in PM gravimetric measurement. 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 $550 \text{ }^\circ\text{C}$ in a pure helium atmosphere for OC, and then at 550 , 650 , and $870 \text{ }^\circ\text{C}$ 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 seconds with an on-line detector equipped with non-dispersive infrared sensor (GXH-3051, Technical Institute, China). The equipment was calibrated using a span gas before each experiment and zero checked after. All filters used were pre-baked at $450 \text{ }^\circ\text{C}$ for 6 hours and equilibrated in a desiccator. Blank samples were also collected and the results were subtracted.

1.3 Data analysis

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 into the forms of gaseous CO, CO₂, total gaseous hydrocarbons (THC) and carbon in PM. In the present study, THC was not measured since most of the gaseous carbon was emitted in the forms of CO or CO₂, and the neglect may result in an error in 1-4% (Roden *et al.*, 2006). It was reported EFs calculated using the carbon mass balance method were comparable to those from direct measurements (Dhammapale *et al.*, 2006). Since it was not necessary to collect all the emitted species and the site of sampling port was flexible in the flue gas, the carbon method was widely used in EF measurements (Dhammapale *et al.*, 2006, 2007; Roden *et al.*, 2006, 2009; Zhang *et al.*, 2000). The detailed description of 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 CO₂ divided by the total amount of carbon released. Since most of the carbon was released in the forms of CO or CO₂, modified combustion efficiency (MCE), defined as CO/(CO₂+CO) ratio (molar basis), was also commonly calculated and used to describe the combustion condition (Dhammapale *et al.*, 2006; Janhäll *et al.*, 2010). In the present study, 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 The influence of fuel mass load

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 $96.8 \pm 0.3\%$, respectively ($p > 0.05$). Measured EF_{PM} s in these three burning circumstances were 3.29 ± 0.11 , 4.65 ± 0.07 , 3.68 ± 0.55 g/kg, respectively. There was no significant difference in these EF_{PM} s ($p > 0.05$). Insignificant differences were also found in measured EF_{OC} and EF_{EC} ($p > 0.05$). 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 total carbon mass fraction in PM (TC/PM, and TC=EC+OC) are two useful parameters in carbonaceous particulate matter study, and commonly used in the source apportionment and climate effect analysis (Bond *et al.*, 2004; Zhi *et al.*, 2009). 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 load. Generally, fine particles dominated the total PM emission from the indoor corn straw burning. Under low, median and high fuel mass load conditions in the present study, mass fractions of PM_{2.1} (PM with diameter less than 2.1 μm, the most close to PM_{2.5} in this study) were 85.9 ± 2.0 , 87.9 ± 1.1 and $87.0 \pm 1.5\%$ of the total, respectively. PM_{1.1} (PM with diameter less than 1.1 μm, the most close 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 ($p > 0.05$).

In the literature, a previous laboratory study on pollutant emissions from simulated open biomass burning reported that the emission concentrations of PM and other pollutants did not vary significantly and the variation in measured EFs was thought to be within the same order of magnitude as the experimental error when fuel mass load ranged from 1 to 10 kg (Grandesso *et al.*, 2011). Without a significant tendency in EF_{PM} , EF_{OC} and EF_{EC} when the mass of burned fuel changed, it was suggested that the effect of mass load on 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). There was much small day to day variation in the consumption amounts of fuel consumed in rural residents' daily lives since the dietary types and persons living in the household were similar at most of the time.

2.2 The influence of burning rate

In the corn straw burning with relatively slow (0.020 ± 0.001 kg/min), median (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 $95.2 \pm 0.6\%$, respectively, decreasing with the increase of fuel burning rate in general ($p > 0.05$). Measured EF_{PM} , EF_{OC} and EF_{EC} 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 significant from those in corn straw burning at the median rate ($p > 0.05$). The ratios of OC/TC and TC/PM were also not significantly different among the burning with these three burning rate levels. It was thought that burning too fast could cause an oxygen limited condition that produced high emissions of various pollutants from the incomplete combustion (Jenkins *et al.*, 1996; Simoneit, 2002; McDonald *et al.*, 2000; Rogge *et al.*, 1998). However, relatively large variations in measurements would result in statistically insignificant difference in measured EFs under different burning rates.

Size distributions of the PM emitted from corn straw burning under different burning rates are compared in Figure 3. $PM_{1.1}$ and $PM_{2.1}$ fractions were 84.8 ± 1.0 and $91.5 \pm 0.9\%$ of the total in the slow burning, were 77.9 ± 2.8 and $87.9 \pm 1.1\%$ in corn straw burning at the median burning rate, and were 53.2 ± 6.1 and $85.0 \pm 1.0\%$ of the total PM in the fast burning experiment. The contribution of fine particles generally declined with the increase of fuel burning rates. This phenomena could be partly explained by the oxygen deficient conditions 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 field was mainly determined by the fire care and skill of the residents during the burning process. In rural residents' daily lives, 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 in the slow and median burning rates in the present study. As mentioned, a fast burning could produce high emissions of incomplete pollutants because of 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 obviously in comparison with the emission from the fast burning.

2.3 The influence of air supply

It is accepted that adequate air supply is required for the stable and high efficient combustion with low emissions 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 the 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 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, was 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 ($\sim 4.0 \text{ m}^3/\text{h}$), median ($\sim 9.0 \text{ m}^3/\text{h}$, a routine situation in rural household biomass burning practice) and enhanced ($\sim 19 \text{ m}^3/\text{h}$) 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 $95.2 \pm 1.1\%$, respectively, which were lower ($p < 0.05$) than $96.1 \pm 0.4\%$ in normal burning condition with median air supply. 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 $0.277 \pm 0.138 \text{ g/kg}$, and were 3.29 ± 2.04 , 0.769 ± 0.543 and $0.319 \pm 0.224 \text{ g/kg}$ in the burning with a high air supply amount, respectively. The results were not significantly different ($p > 0.05$) from those from the burning in the normal situation with median air supply (EF_{PM} , EF_{OC} and EF_{EC} at 4.65 ± 0.07 , 0.879 ± 0.367 and $0.401 \pm 0.029 \text{ g/kg}$, respectively), mainly due to large variations in measurements. Also, the ratios of OC/TC and TC/PM were comparable in the burning under different air supply conditions.

In PM emission, $\text{PM}_{2.1}$ contributed 88.5 ± 3.5 , 87.9 ± 1.1 and $78.9 \pm 1.7\%$ of the total in the burning with low, median and high air supply rates, and the mass fractions of $\text{PM}_{1.1}$ were 53.0 ± 17.4 , 77.9 ± 2.8 and $55.3 \pm 10.2\%$ 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. Slight difference was found in the PM size distributions. In the burning under routine air supply conditions, the distribution was dominated by fine PM with diameter between 0.4 and $0.7 \mu\text{m}$ ($\text{PM}_{0.4-0.7}$) and between 0.7 and $1.1 \mu\text{m}$ ($\text{PM}_{0.7-1.1}$), followed by those with diameter less than $0.4 \mu\text{m}$ ($\text{PM}_{0.4}$). But in the burning with either reduced or enhanced air supply, the most abundant PM fractions were $\text{PM}_{1.1-2.1}$ and $\text{PM}_{0.7-1.1}$ followed by $\text{PM}_{0.4-0.7}$ and $\text{PM}_{0.4}$. Oxygen deficient conditions formed in the combustion chamber with small air supply amount 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 condition that could be sustained by adequate oxygen amount (Hays *et al.*, 2003). In the burning of a high air supply amount, declined mass fractions of these fine $PM_{0.4}$ and $PM_{0.4-0.7}$ might be related to 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 was complicated and the mechanism was 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 influence of air supply amount 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 difference 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 by-product of incomplete combustions. As incomplete pollutants often emitted simultaneously from the burning process, a positive correlation between EF_{PM} and EF_{CO} was sometimes reported in the literature (Bingal *et al.*, 2008; Gupta *et al.*, 1998; Jetter *et al.*, 2012; Venkataraman and Rao, 2001). However, a converse tendency showing decreased PM emission with the increase of 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 correlation 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 Figure 5. Similar insignificant 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 pollutants in the development of emission factors and emission inventory should be in caution (Ballard-Tremere and Jawurek, 1996; Venkataraman *et al.*, 2004).

3. Conclusion

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 3.84 ± 1.02 , 0.846 ± 0.895 and 0.391 ± 0.350 g/kg, respectively. 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 a fast burning or the burning with a low air supply amount could result in oxygen deficient atmosphere, and increased air supply may cool the combustion

temperature, both of which could lead to the change in the formation and emission of carbonaceous particulate matter. Relatively high variation in measurements should be partly responsible for the insignificant difference in this study. 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% as range) and 67.0±14.1% (40.7–85.4%) of the total, respectively. Size distribution of PM could be also influenced by the burning conditions, like burning rate and air supply amounts. However, the reason was not very clear currently. Future study on the influencing factors of PM with different sizes is of interest.

Acknowledgments

Funding for this work was supported by the National Natural Science Foundation of China (No. 41130754, 41001343, and 41001343), Beijing Municipal Government (No. YB20101000101), Ministry of Environmental Protection (No. 201209018) and NIEHS (No. P42 ES016465). Part of Guofeng SHEN's work in Jiangsu Academy of Environmental Sciences was support by the Environmental Protection Department of Jiangsu Province. The authors thank the reviewers for their valuable comments and Dr. Rice for polishing the language.

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Figure 1.

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

Figure 2.

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

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

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

Figure 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.