LABORATORY STUDY OF POLLUTANT EMISSIONS FROM WOOD CHARCOAL COMBUSTION FOR INDOOR SPACE HEATING IN CHINA

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SUMMARY

The climate in rural south China is characterized by hot summers and cold winters, and during the winter season, burning wood charcoal for local heating is widespread. The combustion exhaust is released directly indoors, which increases levels of indoor air pollution. This study evaluates household heating patterns and aims to identify strategies to reduce household air pollution associated with heating. The research choose a common type of wood charcoal fire pan and two kinds of wood charcoal in rural south China to conduct the real-time emission test with a Portable Emission Monitoring System (PEMS) under controlled laboratory conditions. The black wood charcoal (B) was ignited quicker and easier but emitted a large amount of CO while the white wood charcoal (W) was hard to ignite and the burning time was longer. The average burning rate of B could be up to 20±3 g/min, and that of W was about 10±3 g/min. The CO emission factor (EF) of B was 326±61 g/kg fuel, and the PM2.5 EF was 1.5±1.1 mg/kg fuel. The CO EF of W was 138±68 g/kg fuel, and the PM2.5 EF was 2.7±4.3 mg/kg fuel. This study shows that PM2.5 mainly released in the lighting phase, which mainly came from the burning of wood sticks. The PM2.5 emissions of charcoals were lower than PM2.5 from current biomass cookstoves. However, the CO emission was very high at 326g/kg fuel, which was 2 times or even more than 20 times higher than some normal cooking stoves.

INTRODUCTION

Burning wood charcoal for local heating is widespread in regions of rural south China characterized climatically by hot summers and cold winters. Heating during winter provides a comfortable local thermal environment in the household and a harmonious family atmosphere, but these benefits require considerable energy consumption and incur economic cost. The charcoal is commonly burned in a fire pan, which is frequently located in the living room of the household. This traditional heating habit releases the combustion exhaust directly indoors contributing to indoor air pollution in the living space. Air pollution from charcoal combustion contains many different types of hydrocarbons, sulfur compounds, and other trace elements (Kabir et al.,2011; Susaya et al., 2010). Charcoal combustion releases many air pollutant emissions like carbon monoxide (CO), methane (CH4), total non-methane organic carbon (TNMOC), oxides of nitrogen (NOx), and fine particulate matter, among others. CO is
among of the most common emissions from combustion. For instance, the emission factor for CO ranged from 35-198 g kg\(^{-1}\) from a charcoal-fired cookstove, whereas CH\(_4\) emissions from the same stove were only 6.7-7.8 g kg\(^{-1}\) (Bhattachrya et.al, 2002). In addition to causing headaches, dizziness, nausea at lower concentrations, exposure to high levels of carbon monoxide can be fatal. According to multiple studies on CO exposure, exposure to CO in air with the concentration of 20ppm (23 mg/m\(^3\)) for 8h would lead to changes in the human nervous system, which are irreversible (Liang, 2003). Work conducted by researchers at the Beijing Medical University indicates that a guideline concentration limit for one-hour exposure to room concentrations of CO is 15 mg/m\(^3\). According to a concentration standard set by China’s Ministry of Health and 4 other ministries in 1979, the upper limit of indoor CO concentration to be 3 mg/m\(^3\) for one time and the upper limit of average daily concentrations to be 1 mg/m\(^3\) (Liang, 2003).

Additionally, people who are near charcoal combustion can be exposed to respirable suspended particles, including particulate matter with aerodynamic diameter less than 2.5 um (PM\(_{2.5}\)) (Chao and Wong, 2002). Some researchers have demonstrated that exposure to PM\(_{2.5}\) is associated with increased systolic blood pressure in adult women (Baumgartner et.al, 2011). The emission of PM\(_{2.5}\) released by the heating charcoal pan and investigations of real-time CO and PM emissions from charcoal combustion during household heating fill a critical gap in knowledge related to household air pollution associated with solid fuel combustion.

Several studies have measured emissions of CO and PM from charcoal combustion (Bhattachrya et.al, 2002; Taner et.al, 2013). Some analyzed the chemical components in PM\(_{2.5}\) (Taner et.al, 2013). While there have been numerous studies comparing the emission factors of pollutants like CO, CH\(_4\), and PM (in some literature, PM\(_{2.5}\)) from different kinds of wood stoves, biomass stoves or charcoal stoves (Bhattacharya et. al, 2002; Jetter et al. 2012; MacCarty et.al, 2010), very few investigations have been made of real-time emissions of CO and PM from the combustion of charcoal. Real-time emission research could expand our understanding of household air pollution associated with charcoal combustion and inform development of strategies to reduce pollution resulting from household heating practices.

**METHODOLOGIES**

This study focused on measuring CO and PM\(_{2.5}\) emissions from combustion of two types of wood charcoal in rural south China. These two types of wood charcoal were selected because they are very commonly used in rural southern China and because their two heating patterns are different from one another. For example, the white wood charcoal has a higher heating value and combusts longer than the black wood charcoal. The tests were carried out under controlled laboratory conditions, and the experimental protocol was developed based on common heating practices. These practices can be summarized by the intensity of burning and the method for igniting the fire. The Portable Emission Monitoring system (PEMS; Aprovecho Research Center, Oregon, USA) was used to record the real-time emissions from the combustion of charcoal. Indexes like burning rate for every five minutes of two charcoals, real-time CO/PM emission were recorded. The diameter of the fire pan open area was 45 cm, and the diameter of the bottom was 32 cm. The tests were conducted in the Biomass Energy and Environment Engineering Research Center of Beijing University of Chemistry and Technology in April of 2013. The emission test was repeated three times for both kinds of charcoal, black charcoal and white charcoal. The mass of charcoal for each test was 1kg.

The PEMS was used to measure simultaneously the emission in the combustion exhaust of carbon monoxide (CO), carbon dioxide (CO\(_2\)), particulate matter (PM). The CO and CO\(_2\)
sensors recorded the real-time emission data per second. The system was also equipped to collect integrated PM$_{2.5}$ data. When the system operated, the fire pan was ignited in the hood, and the exhaust would go through the duct by a blower, where it then traveled to a sensor box for CO and CO$_2$ analysis.

PM measurements were recorded in real-time with a light-scattering photometer, while gravimetric PM$_{2.5}$ measurements were collected on filters downstream of a cyclone. The Glass fiber filter was in the cyclone separator system and the system would pump exhaust from the duct to go through the cyclone system and then leave the PM$_{2.5}$ on the fiber. Data of PM from PEMS would show the real-time character of emission. Before using, the quartz fiber filter was put in the desiccator/gel dryer over 24 hour to maintain controlled temperature and humidity. After the test, the filter was placed in the same desiccator/gel dryer for over 24 hours. The filter mass, before and after testing, was the average of 10 measurements.

To get the burning rate of charcoals, the fire pan was placed on a scale during emission tests, and the real-time weight of charcoal was recorded. And then burning rate of every five minute could be got. To protect the platform, the fire pan and the scale platform were insulated with cotton and some wood. For all measurements, the scale’s maximum value was never exceeded. The sensitivity of the scale was put the numerical value. Example: 0.1 g.

At the start of each individual test, lighting time was recorded and the charcoal was ignited by wood sticks and a small amount (17-40g) alcohol. The ignition area was located at the approximate center of fire pan. When igniting white charcoal, alcohol was also used because the ignition point of the white charcoal is higher which makes it more difficult to ignite with only a few wood sticks. Before the test, parameters like ambient temperature, and mass of igniting material were also recorded. After the charcoal was ignited, the cyclone system was opened. Then the PM$_{2.5}$ started to accumulate on the filter from this time point forward during the test.

Emission factors (EFs) for CO, CO$_2$, and PM$_{2.5}$ were calculated to compare and evaluated the performance of emission. In this study, the EF represents the mass emission per one kilogram of charcoal burned.

RESULTS AND DISCUSSION

**Burn Rates.** The black wood charcoal (B) was ignited quicker and easier than the white wood charcoal and burned at a higher rate throughout the burn cycle tested. Through 3 repeated tests, the average burning rate of B could be up to $20 \pm 3$ g/5-min interval, and that of W was about $10 \pm 3$ g/5-min interval. The burn rates at the start of the burn cycle were higher for black wood charcoal (Figure 2) than for white wood charcoal (Figure 3), which indicated that black wood charcoal is easier to ignite. Furthermore, over the course of the burn cycle, black wood charcoal reached peak burn rates as high as $35$ g/5-min interval, whereas the peak burn rate for white wood charcoal was only $20$ g/5-min interval. Results presented in Figure 3 also indicate that burn rates of white charcoal were lower and more stable than for black wood charcoal. Intensity of the combustion of charcoal appeared to be influenced by the placement of charcoal in the fire pan. Differences observed between the two types of charcoal with respect to burn rate suggest that real-time pollutant emission rates might also vary between the charcoal type.
Real-time emissions Real-time CO emissions from black wood charcoal followed patterns similar to that of the burning rate (Figure 4). As combustion intensity strengthened, the CO emissions increased, gradually reaching a peak before declining. Real-time PM emission trends for black wood charcoal were not as clearly similar to burn rate patterns. PM emissions appeared to be consistent throughout the burn cycle tested (Figure 4).

The pattern of real-time CO emission from white wood charcoal was also similar to the burn rate pattern observed over the course of the burn cycle evaluated (Figure 5). Like for black wood charcoal, the pattern of real-time PM emissions from white wood charcoal combustion were consistent throughout the burn cycle, with the exception that PM emissions were initially high as the combustion cycle commenced (Figure 5). Once combustion became stable, real-time PM emissions also stabilized at a low level (20 ug/s). During the ignition phase, not pictured in Figure 5, PM emissions were higher than during the more stable combustion phase that followed ignition and may be attributed to combustion of the wood sticks used to ignite the fire rather than the charcoal itself. Because the white wood charcoal was difficult to ignite, more wood sticks were used with white wood charcoal than with black wood charcoal.

CO and PM$_{2.5}$ emission factors (EFs) from combustion of the two kinds of wood charcoals are summarized in Table 1. To put these results in context, several cook stoves were selected from the literature for comparison, including Skirt Stove, charcoal stove (Mali), forced air stoves (MacCarty et al, 2009). [[list stoves and references]]. We selected these stoves for
comparison because the emissions of CO approached the upper limit of stoves listed in literature, while the PM emissions were at a low level. Also, one of the stoves used charcoal as a fuel, providing a good basis for comparison. [fill in with why those stoves were selected for comparison.] The CO EF for black wood charcoal was 326 g/kg fuel, and the PM EF was 1.5 mg/kg fuel. The CO EF of white wood charcoal was 138 g/kg fuel, and the PM EF was 2.7 mg/kg fuel.

Figure 4 Real-time concentration of PM and CO in trail 2.2 (white charcoal). The dotted line stands for the time to open the cyclone pump, also the time to filter the PM2.5.

Table 1 comparison of CO and PM emissions factors from two types of wood charcoal

<table>
<thead>
<tr>
<th>FUEL NO.</th>
<th>TRAIL NO.</th>
<th>Burning rate g/5 min</th>
<th>CO mean g/kg fuel</th>
<th>CO2 mean g/kg fuel</th>
<th>PM2.5 mean mg/kg fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(black)</td>
<td>1.1</td>
<td>23.6</td>
<td>20</td>
<td>381</td>
<td>3564</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>18.9</td>
<td></td>
<td>260</td>
<td>2504</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>18</td>
<td></td>
<td>337</td>
<td>3333</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>6.6</td>
<td></td>
<td>66</td>
<td>1214</td>
</tr>
<tr>
<td>2(white)</td>
<td>2.2</td>
<td>11.5</td>
<td>10</td>
<td>145</td>
<td>4055</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>10.4</td>
<td></td>
<td>202</td>
<td>4072</td>
</tr>
</tbody>
</table>

Compared with CO and PM2.5 emissions from several some cooking stoves selected from the published literature (MacCarty et al, 2009), this traditional way for local heating emits several times more CO and PM2.5 per kg of fuel than some cook stoves, which may increase personal exposure to these pollutants and worsen the associated health risk. According to the National Standard of Indoor Air Quality (GB/T18883-2002), the exposure limit for CO is 10 mg/m^3. The normal volume of a living room in city of China is about 20×2.5 m^3 to 40×2.5 m^3. The frequency of ventilation rate was 0.5 per an hour which is from the ASHRAE Standard 62.1-2007. The average burning rate of black charcoal was 20±3 g/5-min. If the black charcoal burnt for one hour, the average CO concentration could be up to 800-1600 mg/m^3·h. Even the white wood charcoal was beyond the limit from the tests. So if the ventilation rate is not over the supposed value, the concentration of CO is very dangerous. On the other hand, PM2.5 emission factors are lower than those of the stoves selected for comparison.
Table 2: Comparison of Emission Factors for CO and PM$_{2.5}$ from white and black wood charcoal to several cook stoves selected from the literature. (mean ± standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>1 (black charcoal)</th>
<th>2 (white charcoal)</th>
<th>Skirt Stove</th>
<th>Charcoal stove (Mali)</th>
<th>Forced air stoves</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO g/kg fuel</td>
<td>326 ± 61</td>
<td>138 ± 68</td>
<td>54</td>
<td>178</td>
<td>15</td>
</tr>
<tr>
<td>PM (PM$_{2.5}$ for black and white charcoal) mg/kg fuel</td>
<td>1.5 ± 1.1</td>
<td>2.7 ± 4.3</td>
<td>719</td>
<td>409</td>
<td>79</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The main health risk presented by wood charcoal combustion for household heating results from the high level of CO emission. The CO emission was very high at 326 g/kg fuel, which was several times to that of several cooking stoves selected for comparison. One potential way to decrease the CO concentration would to improve the charcoal production method. The CO the white wood charcoal released was just half of that of black wood charcoal. More research could focus on the structure of charcoal even at the molecular level. While the ignition phase of combustion generates peaks in PM emissions, which mainly from the burning of wood sticks, PM emissions over the course of the burn cycle are stable and low. Furthermore, PM EFs are lower for wood charcoal combustion for heating than for biomass combustion for cooking on a per kg basis. One potential approach to reducing PM emissions at the outset of a combustion event could be to ignite the charcoal outdoors to decrease human exposure to PM.

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REFERENCE


