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Effects of moisture content in fuel on thermal performance and emission of biomass semi-gasified cookstove

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ABSTRACT

As the dissemination of improved biomass cookstoves is an ongoing activity, studying the parameters that affect stove performance is important. The objective of this study was to investigate the effect of moisture content (MC) in fuel on stove performance. Wood pellets with MC of 5.9%, 9.4%, 18.2%, and 22.1% were processed and used as fuel in the test. A natural-draft semi-gasified cookstove was employed in this study. Two methods of thermal efficiency calculations were adopted in this study and the results were compared. It was observed that the burning rate, cooking power, and CO and $PM_{2.5}$ emission factors all decreased with the increase of MC in fuel, and the impacts were all statistically significant ($p < 0.05$), while the ratio of quantity of charcoal produced to the quantity of dry fuel stayed at around 26%–27%. The results obtained in this study provided us useful information on the effects of MC in fuel on the performance of a semi-gasified cookstove in the lab and in the field.

Introduction

Approximately 2.4 billion people in the world still burn wood, dung, and other biomass fuels on open fires or traditional cookstoves, leading to low fuel efficiency and high pollution emission (Ruiz-Mercado et al., 2011). Traditional cookstoves consume too much fuel, leading to longer time for fuel collection and deforestation (MacCarty et al., 2010). Subsequent indoor air pollution also results in mortality due to acute respiratory infection and chronic obstructive pulmonary disease (Smith et al., 2000). Therefore, the dissemination of improved cookstoves has been employed to improve indoor air quality in developing countries (Edwards et al., 2004; Qiu et al., 1996). In China, more than 700 million people (of which, two-thirds live in rural areas) rely on solid fuel for cooking and heating (WB, 2013). As estimated by the 2010 Global Burden of Disease report published in the end of 2012, there were approximately 1 million premature deaths per year in China due to household air pollution from solid fuel (Lim et al., 2012). During the 1980s and 1990s, China started the National Improved Stoves Program (NISP), which is among the world's largest and most successful national improved stoves programs (WB, 2013). By the early 1990s, about 130 million improved stoves had been installed in rural areas (Edwards et al., 2004; Sinton et al., 2004). After the NISP ended in the late 1990s, the improved stove market became much more prosperous, and in the last twenty years, 1.6 million clean biomass stoves were produced (WB, 2013).

Biomass semi-gasified cookstoves are based on an improved combustion technology, which is different from other common “improved” stoves, like rocket stoves and other rocket-type wood stoves (Jetter and Kariher, 2009). Gasification burning technology has been recognized as a possible way to cook cleaner in developing countries (Reed and Larson, 1996). Considering the relatively better performance of gasifier stoves tested in a previous study (Jetter et al., 2012), this technology represents a promising development likely to find widespread adoption. Two kinds of semi-gasified cookstoves are being developed in China, natural-draft cookstoves without a fan and forced-draft cookstoves with a fan. The natural-draft semi-gasified biomass cookstove is much cheaper (100 RMB) than the forced-draft cookstoves (more than 500 RMB), is easy to operate, and has a simple structure. In order to design and test the improved cookstoves, it is crucial to understand what kind of factors influence their performance in terms of efficiency and emission of pollutants (Bhattacharya et al., 2002).

Some research studies have been conducted on how fuel moisture content affects the performance of the stoves (Bhattacharya et al., 2002; Bignal et al., 2008; Chomanee et al., 2009; Johansson et al., 2003; L'Orange et al., 2012; Shen et al., 2010; Venkataraman et al.,

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Abbreviations: MC, moisture content; TE, thermal efficiency with charcoal omitted; TE′, thermal efficiency with charcoal corrected; RC, remaining charcoal; BT, boiling time; BR, burning rate; CP, cooking power; $EF_{CO\text{-}D}$, emission factor of CO based on energy delivered; $EF_{PM2.5\text{-}D}$, emission factor of $PM_{2.5}$ based on energy delivered.

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2004; Wei et al., 2012; Yuntenwi et al., 2008). But none of them involved a semi-gasified stove, so the performance study of this stove and fuel combination is of great importance.

The objectives of this study are (1) to investigate the influence of MC in the fuel on the thermal efficiency, charcoal produced, burning rate, cooking power, and CO and $PM_{2.5}$ emission factors; and (2) to compare thermal efficiencies calculated by different methods.

Material and methods

Stove

The natural-draft stove tested in this study has two metal walls without thermal insulation material between the walls (Fig. 1). This kind of stove is often called a TLUD (top-lit up-draft) stove by researchers outside China.

The main improvement of the semi-gasified technology is the separation of the draft channel into primary air and secondary air, resulting in a second combustion zone at the top of the stove. The semi-gasified stove evaluated in this study was batch-loaded with fuel and had a cylindrical combustion chamber, a primary air channel in the bottom, and a secondary air channel around the top of the stove. The batch of fuel is ignited on the top, and then the primary combustion (pyrolysis) zone moves downward through the fuel bed heating and gasifying the fuel, and this is where the name semi-gasified originated. Primary air is supplied from the bottom of the combustion chamber, and flows upward through the porous fuel bed to the pyrolysis zone. Flammable gases, mainly CO, are produced in the gasification zone and burned in the second combustion zone. The secondary air supplied from the top channel can ensure mixing of burned gas with secondary air in order to prevent high CO emission (El may et al., 2013). When the gasification progresses smoothly, a visible flame exists near the secondary air channel.

Fuel

The fuel used in all tests consisted of commercial cylindrical wood pellets (Beijing Sheng Chang Bio-energy S&T Co. Ltd.). The diameter of the pellets was 0.8 cm and the length was 2 cm. All fuels were kept in a cool and dry place, and away from direct sunlight. The MC of the fuel was measured before the test, according to the method described by Yuntenwi et al. (2008).

The original MC of fuel was 9.4% and the lower heating value (LHV) was 16.7 MJ/kg. The proximate and ultimate analyses of the fuel were determined by the Thermal Engineering Laboratory of Tsinghua University and the Analysis and Test Center of Beijing University of Chemical Technology (Table 1).

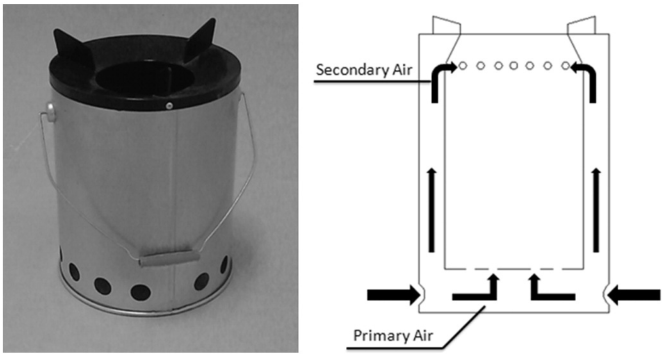

Fig. 1. Stove picture and structural sketch.

Table 1
Fuel proximate and ultimate analyses (dry basis).

% Ultimate		% Proximate	
Carbon	48.13	Ash	6.96
Hydrogen	6.143	Volatile matter	74.73
Nitrogen	0.091	Fixed carbon	17.06
Sulfur	0.049		

Moisture control

The MC of fuel in this study was adjusted as described by Bhattacharya et al. (2002). The MC was calculated on a wet basis. A certain amount of water was added to obtain a higher MC than original fuel. For levels lower than the original MC, fuel was dried totally and then a certain amount of water was added. To achieve equilibrium MC, all fuel was kept in watertight lockers for 2 weeks and was turned upside down every day. Final MCs of fuel were adjusted to 5.9%, 9.4%, 18.2%, and 22.1%, respectively. MC higher than 25% was not investigated because, at this MC level, the fuel pellets became loose and disintegrated.

Emission measurement system

In this study, the emissions of the stoves were measured by an Emission Measurement System made by Aprovecho Research Center in the US (Fig. 2). All the pollutants emitted by the stoves were collected into a hood and diluted in the S-shaped pipe. CO was measured by an electrochemical cell. A cyclone separator was employed to separate particulate matter less than 2.5 μm in diameter. The required flow rate through the cyclone was 16.7 L/min, which was controlled by a critical orifice and vacuum pump. Binderless glass fiber filter with a diameter of 4 in. was used to collect the $PM_{2.5}$, and a desiccator was used to control the moisture of the filter. The CO monitor was calibrated with standard gas (Beijing Zhaoge Gas Technology Co., Ltd.) once a month. The flow rate of the $PM_{2.5}$ measurement system was checked and the cyclone was cleaned before each test to make sure that there was no particle remaining. The weight of filter was measured by an electronic balance (Mettler Toledo, AL204-IC) with resolution of 0.0001 g.

Performance evaluation

Chinese standard testing methods (BMAQTS, 2008) were used for the stove performance evaluation in this study, with the slight modification that the charcoal left after each test was weighed for subsequent calculation. The pot used was a cylindrical aluminum pot of 28 cm diameter. The stove was tested at least 3 times on each fuel moisture level to satisfy the upper limit of coefficient of variation (Cov), which was set as 30% in this study. All data were processed by SPSS 18. Analysis of variance (ANOVA) was applied in the analysis. The significance level of the statistical analysis was $p = 0.05$ unless indicated otherwise.

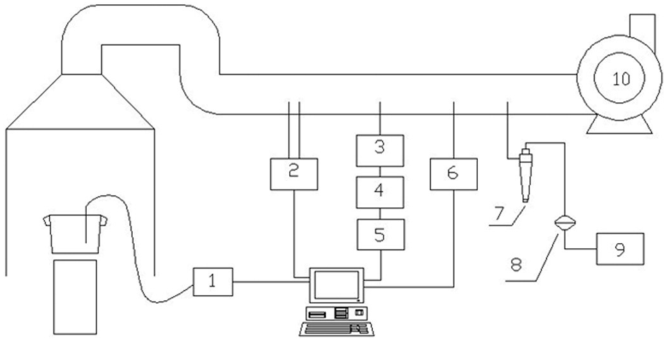

Fig. 2. Emission measurement system. 1, Thermocouple; 2, flow rate sensor; 3, real-time PM sensor; 4, CO sensor; 5, CO_2 sensor; 6, temperature sensor; 7, cyclone; 8, filter container; 9, vacuum pump; 10, draught fan.

Thermal performance evaluation

The stove was fully loaded with pre-weighed fuel, and alcohol was used as fire starter. Five liters of water were heated to boil and kept boiling until the fuel was exhausted. Then, the weight of the water and the remaining charcoal was measured, and the time taken was noted. With the data collected, thermal efficiency, cooking power, boiling time, and burning rate were studied as thermal performance indicators.

Fuel savings was the initial motivation and the most compelling reason for improved biomass stove dissemination in China (Qiu et al., 1996; Sinton et al., 2004), Guatemala (Boy et al., 2000; Granderson et al., 2009), and India (Aggarwal and Chandel, 2004), so thermal efficiency was considered as the main indicator of the stove's performance especially when stoves were chosen for the dissemination program. Thermal efficiency is defined as the ratio of effective energy to the thermal energy generated by fuel in the stove. There are two different calculations to get thermal efficiency. In one calculation, the energy in the charcoal is omitted from the calculation, assuming that the charcoal energy is consumed during the test, which is named "charcoal omitted" in this paper. In the other calculation, the energy released by the fuel during the test is calculated as the fuel energy released minus the energy embodied in the remaining charcoal, which is named "charcoal corrected" in this paper. The employment of the two calculations is still under discussion in the stove research community and establishment of an international protocol is under way. In this study, both calculations were conducted and marked as TE and TE′, respectively, according to Eqs. (1) and (2).

$$\mathrm{TE} = \left[E_{\mathrm{delivered}}/\left(E_{\mathrm{dry\ fuel}}-E_{\mathrm{MC}}\right)\right] \times 100\% \tag{1}$$

$$\mathrm{TE}' = \left[E_{\mathrm{delivered}}/\left(E_{\mathrm{dry\ fuel}}-E_{\mathrm{MC}}-E_{\mathrm{char}}\right)\right] \times 100\% \tag{2}$$

Where: $E_{\mathrm{delivered}}$ refers to energy (kJ) absorbed by the water in the pot used for temperature change and water evaporated. $E_{\mathrm{dry\ fuel}}$ means energy (kJ) available from the dry fuel. E_{MC} means energy (kJ) required to evaporate the MC in fuel. E_{char} represents the energy (kJ) that remained in the charcoal, calculated by the mass of charcoal multiplied by the LHV of the charcoal.

The charcoal was weighed after each test and the remaining charcoal (RC) was calculated by the following Eqs. (3) and (4) as a ratio of the mass of charcoal to the mass of fuel on wet basis and on dry basis. Two other thermal performance indicators, burning rate (BR) and cooking power (CP) were calculated by the following Eqs. (5) and (6)

$$\mathrm{RC}_{\mathrm{wet\ basis}} = \left(W_{\mathrm{char}}/W_{\mathrm{wet\ fuel}}\right) \times 100\% \tag{3}$$

$$\mathrm{RC}_{\mathrm{dry\ basis}} = \left(W_{\mathrm{char}}/W_{\mathrm{dry\ fuel}}\right) \times 100\% \tag{4}$$

$$\mathrm{BR}\left(\mathrm{g\ min}^{-1}\right) = W_{\mathrm{wet\ fuel}}/T_{\mathrm{test}} \tag{5}$$

$$\mathrm{CP(Watt)} = E_{\mathrm{delivered}} \times 10^{3}/T_{\mathrm{test}} \tag{6}$$

Where: W_{char} refers to the mass of the remaining charcoal at the end of the test (g). $W_{\mathrm{wet\ fuel}}$ means the mass of the fuel consumed in the whole test (g) on wet basis. $W_{\mathrm{dry\ fuel}}$ means the mass of the fuel consumed on dry basis. T_{test} represents the time to complete one test (min in Eq. (5) and s in Eq. (6)).

Emission performance evaluation

In February 2012, the International Organization for Standardization (ISO) International Workshop Agreement (IWA) (2012) was built as a temporary guideline and provided a framework for rating cookstoves by a series of performance indicators including fuel use (efficiency), total and indoor emissions (CO and $PM_{2.5}$), and safety. CO is one of the primary products of incomplete combustion and can cause an increase in intrauterine mortality and low birthweight in infants (Smith et al., 2000). $PM_{2.5}$ can travel farther into the lungs than large particles and is thus believed to have an adverse effect on human health (Bergauff et al., 2009). Following the IWA, CO and $PM_{2.5}$ were selected in this study as the main indicators to demonstrate the emission of the stove.

Emission factors of CO ($EF_{\mathrm{CO\text{-}D}}$) and $PM_{2.5}$ ($EF_{\mathrm{PM2.5\text{-}D}}$) representing the weight of pollutants emitted per megajoule of energy delivered to the cooking pot were calculated according to Eqs. (7) and (8) in energy-based units.

$$\mathrm{EF}_{\mathrm{CO-D}}\left(\mathrm{g\ MJ_D^{-1}}\right) = W_{\mathrm{CO}}/E_{\mathrm{delivered}} \times 10^{3} \tag{7}$$

$$\mathrm{EF}_{\mathrm{PM_{2.5}-D}}\left(\mathrm{mg\ MJ_D^{-1}}\right) = W_{\mathrm{PM2.5}}/E_{\mathrm{delivered}} \times 10^{3} \tag{8}$$

where: W_{CO} (g) and $W_{\mathrm{PM2.5}}$ (mg) mean the weight of CO and $PM_{2.5}$ emitted in one test, respectively.

Results and discussion

According to the rating system against tiers of performance provided by IWA (2012), the relative performance indicators in this study were rated as follows. During the test using fuels with different MCs, the range of $EF_{\mathrm{CO\text{-}D}}$ was from 4.4 g/MJ_D to 2.7 g/MJ_D, which all fell into Tier 4; in terms of $EF_{\mathrm{PM2.5\text{-}D}}$, the range was between 581.7 mg/MJ_D and 194.8 mg/MJ_D, and the corresponding rating changed from Tier 1 to Tier 2; As for the thermal efficiency, TE varied from 24.2% to 28.6%, located in Tier 1 or Tier 2, while the TE′ changed from 40.6% to 48.9%, ranking in Tier 3 or Tier 4.

Thermal efficiency and remaining charcoal

Thermal efficiencies calculated by two different methods were compared in Figs. 3a and b. As shown in Figs. 3a and b, as the level of MC increased from 5.9% to 18.2%, both TE (Fig. 3a) and TE′ (Fig. 3b) increased from 24.2% to 28.6% and from 40.6% to 48.9%, respectively. Slight decreases in both cases were found at MC of 22.1%, but the effect of different MCs (between 5.9% and 18.2%) on TE and TE′ were both statistically significant ($p < 0.01$). According to the results, when using fuel with different MCs, it can be observed that TE′ calculated with charcoal corrected was more than 15 percentage points higher than TE calculated with charcoal omitted, indicating that the calculation method affected the thermal efficiency significantly.

Bhattacharya studied the effect of MC on efficiencies of biomass-fired cookstoves and the efficiency was calculated in the same way as TE′. He found that the efficiencies of the RTFD-improved charcoal stove, the Indian "Harsha" stove, and the traditional Vietnamese stove were all reduced with an increase in fuel MC from approximately 10% to 25% (Bhattacharya et al., 2002). An opposite variation trend of thermal efficiency was observed in this study. This may be because in the study conducted by Bhattacharya et al. (2002), the higher heating value was used to calculate the denominator to get thermal efficiency and the fact that energy available from the fuel was not corrected by the MC.

Charcoal-making is one of the stove functions in places where charcoal is used as a soil amendment, which makes the remaining charcoal as one of the performance indicators of the stove. During this study, the effect of fuel MC on charcoal production was investigated. As the MC of fuel increased from 5.9% to 22.1%, a significant decrease of $RC_{\mathrm{wet\ basis}}$ from 26.0% to 20.9% ($p < 0.01$) (Fig. 4) was observed, but the $RC_{\mathrm{dry\ basis}}$ was around 26.5% and not affected by the MC in the fuel

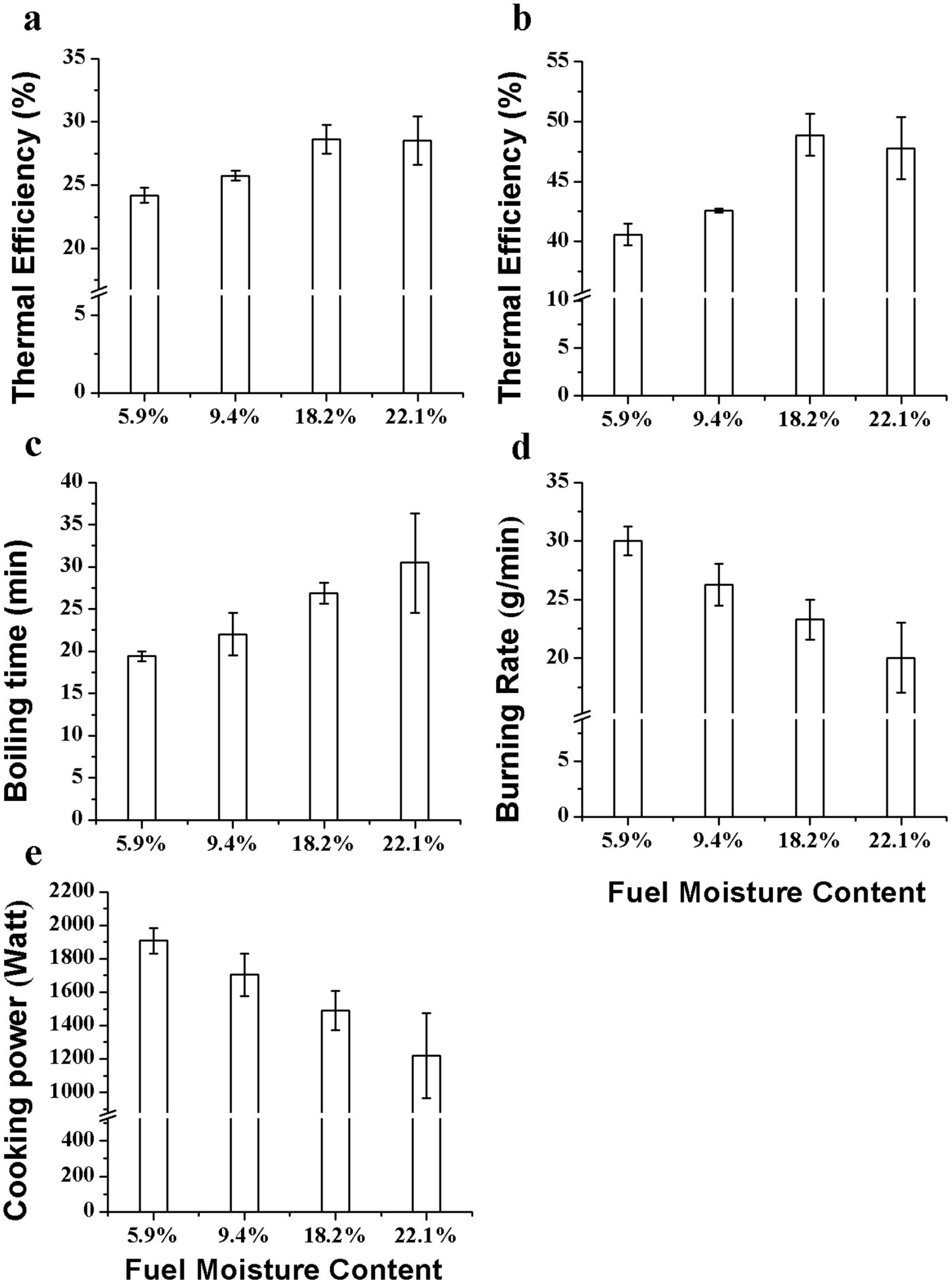

Fig. 3. The trend of (a) TE calculated with charcoal omitted; (b) TE′ calculated with charcoal corrected; (c) BT; (d) BR; and (e) CP at different fuel MCs.

($p > 0.05$). The higher level of MC in fuel resulted in less dry fuel actually burned in the stove, and the unchanged $RC_{\text{dry basis}}$ indicated that the difference in MC of the fuel did not change the transition process of dry fuel to charcoal. As a result, more charcoal can be obtained by burning drier fuel where the cookstove in this study is utilized in order to satisfy the demands of charcoal-making while cooking.

Boiling time, burning rate, and cooking power

Boiling time (BT), burning rate (BR), and cooking power (CP) at different fuel MCs are shown in Figs. 3c–e. BT indicates how fast the water boils. BR and CP are both indicators related to the combustion intensity, meaning how fast the fuel burns and how fast the energy is delivered, respectively.

In this study, burning rate decreased by 33.3% from 30.0 g/min at 5.9% MC to 20.0 g/min at 22.1% MC, and the cooking power was reduced by 36.1% from 1910 W at 5.9% MC to 1220 W at 22.1% MC (Figs. 3d and e). Both factors were negatively affected by the MC, and the impacts were statistically significant ($p < 0.001$). The presence of water in the fuel significantly slowed the burning process in the combustion chamber, which was consistent with the report of L'Orange et al. (2012). The fuel in the combustion chamber was burnt gradually from the top

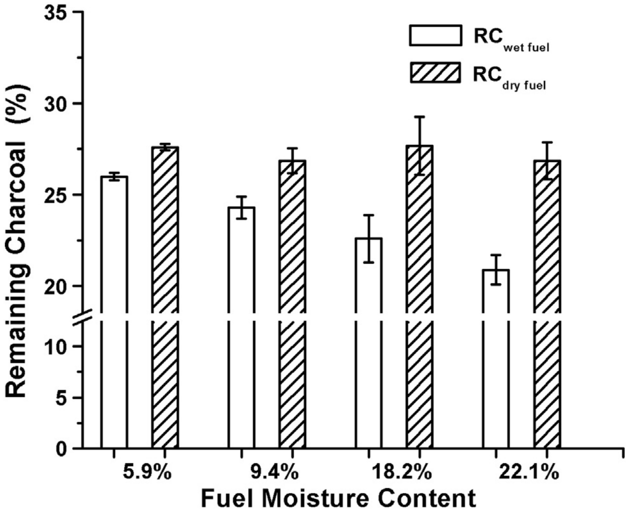

Fig. 4. The trend of $RC_{wet\ fuel}$ based on wet fuel and $RC_{dry\ fuel}$ based on dry fuel at different fuel MCs.

down, and the existence of water in the fuel slowed the combustion and reduced the temperature achieved in the burning zone (McKendry, 2002), leading to less fuel gasified at one moment. Therefore, the combustion intensity was reduced.

Boiling time increased by 57.2% from 19.4 min at 5.9% MC to 30.5 min at 22.1% MC (Fig. 3c), and the impact of MC was statistically significant ($p < 0.01$). This is due to the negative correlation between combustion intensity and MC. The energy of fuel was released at a lower rate, leading to the longer time required to boil the water.

Emission factors of CO and $PM_{2.5}$

Considering the short-term and long-term health effects, CO and $PM_{2.5}$ were monitored as the main emission factors in this study. The results are presented in Fig. 5.

In this study, the $EF_{CO\text{-}D}$ decreased by 38.6% from 4.4 g/MJ_D at 5.9% MC to 2.7 g/MJ_D at 22.1% MC (Fig. 5a). According to the data analysis, the increase of MC in fuel resulted in lower emission factors of CO and $PM_{2.5}$. The effects of MC on emission factors were both statistically significant ($p < 0.05$), although the effect became weaker at higher MC. A negative correlation between MC in fuel and CO emission factor was obtained, which was in contrast to previous investigations. Wei et al. (2012) found that CO emission increased at higher MC of fuel in the experiments on a brick wok stove using firewood chips with three moisture levels. Bhattacharya et al. (2002) found the same trend by using firewood. In this study, $EF_{PM2.5\text{-}D}$ was reduced by 66.5% from 581.7 mg/MJ_D at an MC level of 5.9% to 194.8 mg/MJ_D at an MC of 22.1% (Fig. 5b). A similar significantly negative correlation between MC and PM emission factor was also found in Shen et al.'s report (Shen et al., 2010).

The stove type is the key reason why the relationships between MC and emission factors were in contrast to the results in the paper conducted by Wei et al. (2012) and Bhattacharya et al. (2002), but were the same with Shen et al.'s finding (Shen et al., 2010). In the study conducted by Bhattacharya et al. (2002), the two biomass stoves used were rocket-type stoves (Jetter and Kariher, 2009) with a cylindrical combustion chamber and an opening on one side of the stove for refueling. In the report of Wei et al. (2012), the tests referring to the moisture influence were conducted using firewood chips, and the stove used was a brick wok stove, which was also a rocket-type stove. When firewood chips with higher moisture content were burning in the rocket-type stove, the presence of water led to lower temperatures in the combustion chamber, causing white thick smoke to escape out of the stove without being burned. In our experiment, a semi-gasified cookstove was used, which was the same type of stove used in Shen et al.'s report (2010). This kind of stove was batch-loaded and was lighted on the top of the fuel, and it had a secondary air-feeding system for burning the gasification products including CO and $PM_{2.5}$. The presence of water lowered the temperature in the combustion chamber, but once the stove was lighted, the charcoal produced on the top of the fuel kept the temperature high enough to gasify the fuel below, producing combustible products, which burned with the air provided by the secondary air-feeding system. Water in the fuel slowed down the burning process and increased gas residence time in the combustion zone (Baldwin, 1987), leading to a more complete combustion and less pollutants emitted.

However, fuel that was too wet was hard to ignite, and more starting fuel was needed. Another impact on performance was the condensation of excess moisture on the bottom of the pot, which could drop into the combustion chamber or fuel bed, affecting the performance. That might be the reason why the emission factors measured at 22.1% MC had a bigger standard deviation.

Practical implication

Two kinds of thermal efficiency calculations were undertaken in this study, reflecting the same trends based on the MC in fuel but yielding different test results. The huge difference in the test results highlight

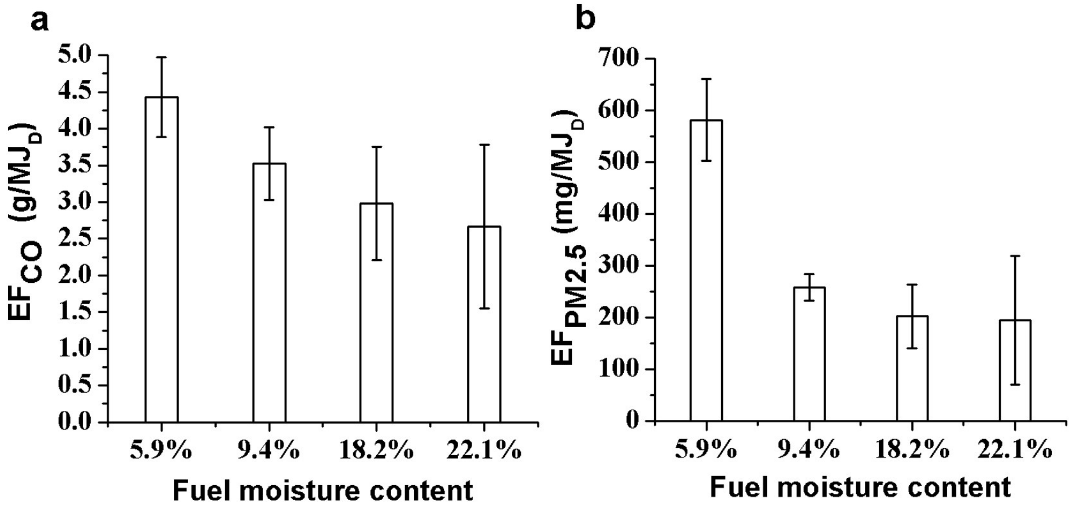

Fig. 5. Emission factors of stove: (a) $EF_{CO\text{-}D}$; (b) $EF_{PM2.5\text{-}D}$ at different fuel MCs.

the essential role of the calculation method in the performance evaluation of cookstoves. Calculated with charcoal corrected, TE′ was more than 15 percentage points higher than TE calculated with charcoal omitted, which indicated that the energy in the charcoal played an important role in the comparison between testing results calculated by different methods.

The significant impact of MC in fuel on the emission factors observed in this study reminds us of the vital role of MC in the performance evaluation. So the future testing protocol should specify or restrict the MC of the fuel to be used in the performance evaluation, to avoid any bias resulting from different MC levels. In future studies, especially in the estimation of total amount of pollutant in certain areas based on the emission factors, it is strongly recommended that the MC of the fuel in the study region should be considered in testing and prediction models to minimize the error caused by fuel MC.

Conclusions

The effects of MC in fuel on the performance of a semi-gasified cookstove were analyzed in this study. It was found that the increase of MC reduced the burning rate, cooking power, and CO and $PM_{2.5}$ emissions of the cookstove while increasing the boiling time. The same variation trends of thermal efficiencies for different MCs were obtained but the numerical difference was large due to the different calculation methods. These results provided us useful information on the vital role of MC in fuel in the performance evaluation of cookstoves and the regional prediction of total emission in the future.

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