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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.,

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).

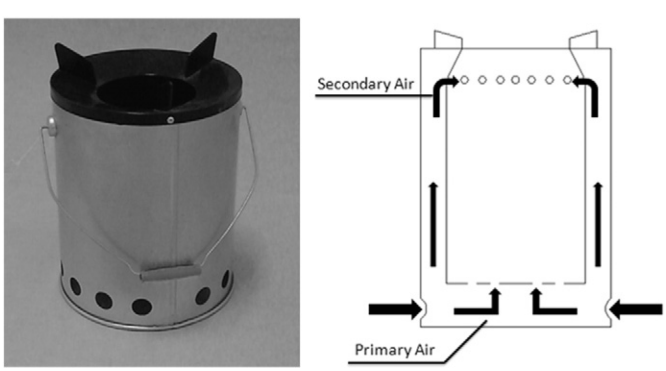

Fig. 1. Stove picture and structural sketch.

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.

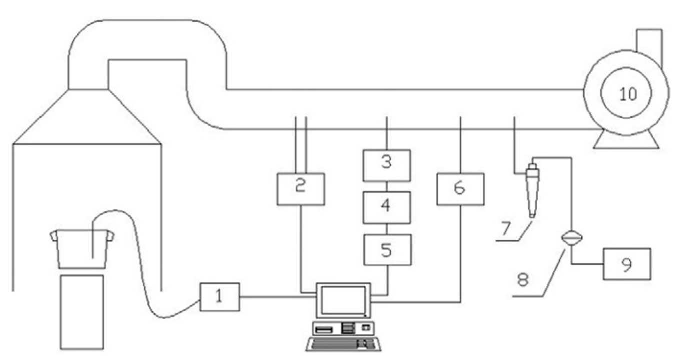

Fig. 2. Emission measurement system. 1, Thermocouple; 2, flow rate sensor; 3, real-time PM sensor; 4, CO sensor; 5, CO_2 sensor; 6, temperature sensor; 7, cyclone; 8, filter container; 9, vacuum pump; 10, draught fan.