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The impact of cookstove operation on $PM_{2.5}$ and CO emissions: A comparison of laboratory and field measurements[☆]

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ABSTRACT

Inefficient biomass combustion in traditional cookstoves generates high levels of household air pollution (HAP) that is associated with numerous adverse environmental and human health conditions. Many cookstoves have been evaluated using laboratory tests, but past studies revealed discrepancies between laboratory and field measurements. Fuel re-loading, a common operation in actual use but not required in the laboratory test, might be a contributing factor to this laboratory-field gap. In this study, we evaluated the pollutant emissions performance of a semi-gasifier cooking stove using both laboratory and field measurements. Emission factors and real-time properties of CO and $PM_{2.5}$ were separately measured during the following 4 phases of a typical cooking event: lighting, stable combustion, fuel re-loading and post fuel re-loading. We quantified the CO and $PM_{2.5}$ contributions to total cooking event emissions in each phase. We found over 70% lower $PM_{2.5}$ emissions and 60% lower CO emissions during 3 no re-loading laboratory tests compared with all 16 field tests. Lighting generated 83.8% ± 15.6% of the total $PM_{2.5}$ and 39.1% ± 7.8% of the total CO in laboratory tests without fuel re-loading, and 57.8% ± 33.5% and 37.9% ± 21.2% of the total $PM_{2.5}$ and CO in field tests, respectively. On average, fuel re-loading led to 29.1% ± 30.8% of $PM_{2.5}$ emissions and 24.9% ± 22.6% of CO emissions in 16 field tests, which also contributed to significant discrepancies between laboratory and field-based emissions. According to the ISO IWA tiered stove ratings for emissions, fuel re-loading led to at least one tier lower ranking in both laboratory and field cookstove tests. Fuel re-loading could be an important factor causing laboratory-field discrepancy of emissions, thus it could be considered in future cookstove selection and intervention projects.

1. Introduction

Approximately 2.8 billion people worldwide rely on solid fuels to meet their daily cooking needs (Adair-Rohani et al., 2016; Bonjour et al., 2013; IEA, 2016). Inefficient and incomplete combustion of solid fuels in traditional cookstoves emits high concentrations of air pollutants (Naeher et al., 2007; Zhang et al., 2000). Exposure to household air pollution is a leading contributor to the global burden of disease, accounting for 2.8 million premature deaths in 2015 (Cohen et al., 2017). It also contributes to ambient air pollution, adding further to the burden of disease associated with air pollution exposures and potentially impacting global and regional climate change and atmospheric visibility (Bond et al., 2013; Chafe et al., 2014; Ramanathan and Carmichael, 2008).

National and international organizations support initiatives to reduce household air pollution from biomass burning in more than 40% of households worldwide (GACC, 2012; GACC, 2016; IEA, 2016; Smith and Keyun, 2010; Urmee and Gyamfi, 2014). The Global Alliance for Clean Cookstoves (GACC) has set a goal to deliver 100 million clean cookstove to households in developing countries by 2020. In alignment with these goals, the Chinese government aims

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to deliver 40 million cookstoves (meeting ~40% of the GACC target) (GACC, 2016). Yet many improved biomass cookstoves have not achieved substantial reductions in pollutant emissions under conditions of real-world use, relative to the traditional cooking technologies they replace, and therefore fail to realize the intended benefits for energy conservation, environmental protection, and health (Aung et al., 2016; Balakrishnan et al., 2015; Mortimer et al., 2017). To address this issue, identifying features of stove performance (i.e. efficiency, pollutant emissions) under conditions of actual use that could be robustly replicated should be considered in laboratory tests during stove design. Thus, stoves performing well in the laboratory would have equivalent performances in homes.

Many previous studies have evaluated the energy efficiency and pollutant emission factors of cookstoves tested using laboratory testing protocols (Arora et al., 2014; Carter et al., 2014; Kirch et al., 2016; Kirch et al., 2018; Kshirsagar and Kalamkar, 2014; MacCarty et al., 2010; Obi et al., 2016; Xie et al., 2018). Laboratory testing protocols frequently simplify operating conditions, and have led to identification of technological parameters that influence cookstove performance (Kirch et al., 2018; Obi et al., 2016). However, there is increasing emphasis on the use of field measurements to carry out a well-rounded evaluation of stove performance, given discrepancies consistently observed between laboratory and field performance (Garland et al., 2017; Jagger et al., 2017). Recent field studies have conducted measurements during cooking activities under conditions of actual use, or measurements that closely approximate conditions of actual use (Du et al., 2017; Shen and Xue, 2014; Medina et al., 2017; Wei et al., 2014). Several studies conducted comparisons between laboratory and field results and gave insights into the laboratory-field gap, to promote stove development and evaluation (Chen et al., 2012; Du et al., 2018; Roden et al., 2009; Shan et al., 2017). However, studies that explicitly investigated one or more specific influencing factors leading to differences between those measurements are rare. Lack of understanding of real-world factors that influence performance suggests that cookstove measurements, as widely conducted in laboratories, have limited capacity to inform household energy intervention development.

Nowadays, batch-fed cookstoves are prevalently used for solid fuels, especially biomass fuels. Here "batch-fed" is defined as a certain amount of fuel that need to be loaded in the stove before lighting, and fuel might be re-loaded to support long duration combustion. Lighting and fuel re-loading are the two common operations of these cookstoves. Some laboratory-based studies have explored the effect of lighting on stove performance but ignored fuel re-loading (Carter et al., 2014; Leavey et al., 2017). However, re-loading could lead to emission aggravation in actual use (Roden et al., 2009). Further exploration of these operations, especially fuel re-loading, might supply better understanding of laboratory-field discrepancy.

In this study, we investigated the impact of real-world operational parameters including lighting and fuel re-loading, on cookstove emissions performance in the laboratory and field for a semi-gasifier cookstove designed to burn biomass pellets. Our analysis of stove testing conditions considered several factors anticipated to impact pollutant emissions of particulate matter with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) and carbon monoxide (CO) emission factors. Namely, we compared laboratory- and field-measured $PM_{2.5}$ and CO emission factors by phase of cooking (i.e. lighting, stable combustion, fuel loading and post fuel re-loading) and with respect to total event fuel consumption, cooking event duration. We performed 6 laboratory tests using the Chinese water boiling test (C-WBT) and 16 field measurements of in-use cooking. The CO and $PM_{2.5}$ emission factors (EFs), real-time emissions, and their relative contribution to defined cooking phases were compared to assess the influence of different operation parameters for this type of cookstove. This study contributes detailed information about the impact of lighting and re-loading occurring during actual cooking on cookstove performance. The methods and results could inform future cookstove design, laboratory testing protocols and improve cookstove selection for large-scale intervention.

2. Methods

2.1. Cookstove and fuel

We evaluated the Tsinghua University (THU) cookstove, which is a forced draft, semi-gasifier cookstove with distinguishing design features including controllable fuel loading and re-loading, air supply, and electric ignition. Fuel loading and re-loading are conducted by rotating the re-loading crank, and lighting is conducted by turning up an electric coil heater inside the combustion chamber. The design process and incorporation of several unique features, is summarized in the Supporting Information (Fig. S1) and described in detail elsewhere (Shan et al., 2017).

We burned the same wood pellets in both laboratory and field measurements to minimize potential variability due to differences in fuel type (Fig. S2). These pellets were made from compressed biomass and were approximately 8 mm in diameter by 30 mm length.

2.2. Measurement system

The measurement system included two parts: a flue gas analyzer (Testo 350, Testo Inc, Germany) that directly sampled gas and measured real-time concentrations of CO and greenhouse gas CO_2, and a dilution system used for cooling flue gas and decreasing particulate mass concentration down to the instrument's measurement range (Figure S3).

The dilution system was designed to measure real-time concentrations and pollutant emissions in both laboratory and field experiments (Shan et al., 2017). In the system, $PM_{2.5}$ real-time concentration was measured by a laser dust sampler (DustTrak 8530, TSI Inc, USA) with a 37 mm polytetrafluoroethylene (PTFE) filter (2 μm pore size, Pall Corporation, USA) in it for gravimetric $PM_{2.5}$ measurements. We assumed that the optical properties of $PM_{2.5}$ was invariable, which may lead to some uncertainties. The airflows passing through the flue gas analyzer and the laser dust sampler were controlled by the two devices, respectively. The clean airflow in the system was controlled by a mass flow controller (D-600CD, Dexin Inc., China). More details about the measurement system could be seen in Fig. S3.

Briefly, flue gas was exhausted through the chimney and sampling probes were placed in the center of the chimney near its outlet. At the start of each measurement, we first sampled the background air for approximately 30 min to measure background concentrations of carbon dioxide (CO_2) and pollutants of interest (CO and $PM_{2.5}$). We then commenced the emissions measurements concurrently with cookstove ignition.

2.3. Testing sites and experimental matrix

We conducted controlled laboratory measurements in the Tsinghua Rural Energy and Environment Laboratory in peri-urban Beijing. We measured emissions from the installed semi-gasifier cookstove during 6 tests. These tests were divided into two groups: Group A (L1-L3) and Group B (L4-L6). Tests in Group A were conducted under identical lighting and air supply modes, with no fuel addition included in the testing protocol. Group B tests were identical to Group A tests in lighting and air supply modes, but