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Comparison of air pollutant emissions and household air quality in rural homes using improved wood and coal stoves

Wei Du [a], Guofeng Shen [a, *], Yuanchen Chen [b], Xi Zhu [a], Shaojie Zhuo [a], Qirui Zhong [a], Meng Qi [a], Chunyu Xue [c], Guangqing Liu [c], Eddy Zeng [d], Baoshan Xing [e], Shu Tao [a, **]

[a] Laboratory of Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing 100871, PR China
[b] College of Environment, Zhejiang University of Technology, Hangzhou, Zhejiang 310014, China
[c] Department of Environmental Science and Technology, Beijing University of Chemical Technology, Beijing 100029, PR China
[d] School of Environment, Guangzhou Key Laboratory of Environmental Exposure and Health, Guangdong Key Laboratory of Environmental Pollution and Health, Jinan University, Guangzhou 510632, China
[e] Stockbridge School of Agriculture, University of Massachusetts, Amherst, MA 01003, United States

HIGHLIGHTS

- Field measurements were conducted to quantify air pollutant emissions and fuel consumptions.
- Impacts of replacing coal with wood on household air pollution and climate were addressed.
- Wood combustion in gasifier stoves produced more EC and $PM_{2.5}$ than coal combustion did.
- Benefits related to climate change are significantly decreasing CO_2 and CH_4 emissions and increasing OC.
- Significantly higher indoor air pollution than outdoor air was found although stoves are equipped with chimneys.

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ABSTRACT

Air pollutant emissions, fuel consumption, and household air pollution were investigated in rural Hubei, central China, as a revisited evaluation of an intervention program to replace coal use by wood in gasifier stoves. Measured emission factors were comparable to the results measured two years ago when the program was initiated. Coal combustion produced significantly higher emissions of CO_2, CH_4, and SO_2 compared with wood combustion; however, wood combustion in gasifier stoves had higher emissions of primary $PM_{2.5}$ (particles with diameter less than 2.5 μm), Elemental Carbon (EC) and Organic Carbon (OC). In terms of potential impacts on climate, although the use of wood in gasifier stoves produced more black carbon (6.37 vs 910 gCO_2e per day per capita from coal and wood use) and less SO_2 (-684 vs -312), obvious benefits could be obtained owing to greater OC emissions (-15.4 vs -431), fewer CH_4 emissions (865 vs 409) and, moreover, a reduction of CO_2 emissions. The total GWC_{100} (Global Warming Potential over a time horizon of 100 years) would decrease by approximately 90% if coal use were replaced with renewable wood burned in gasifier stoves. However, similar levels of ambient particles and higher indoor OC and EC were found at homes using wood gasifier stoves compared to the coal-use homes. This suggests critical investigations on potential health impacts from the carbon-reduction intervention program.

1. Introduction

In many developing countries and regions, solid fuels, such as coal and biofuels, are primary energy resources for cooking and heating. Those solid fuels are often burned in low efficiency stoves and produce large amounts of air pollutants such as fine $PM_{2.5}$ (particles with a diameter of less than 2.5 μm), black carbon (BC), and SO_2. In China, 36% of primary $PM_{2.5}$ and 53% of BC originate from residential fuel combustion (Shen et al., 2013; Wang et al., 2012; Huang et al., 2014). People in areas relying on solid fuel use

* Corresponding author.
** Corresponding author.
E-mail addresses: gfshen12@gmail.com (G. Shen), taos@pku.edu.cn (S. Tao).

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often suffer from heavy household air pollution (HAP) (Ezzati et al., 2000; Albalak et al., 2001; Mumford et al., 1989). Exposure to HAP has been recognized as a major environmental risk factor that is responsible for many respiratory and cardiovascular diseases and premature deaths (Lee et al., 2012; Zhang and Smith, 2007; Forouzanfar et al., 2015). According to the WHO (2014), nearly 4.3 million premature deaths around the world in 2012 were due to exposure to HAP.

Current efforts are being aimed at deploying clean fuel and/or clean stoves to alleviate air pollution, and consequently to address climate change and to protect human health. Deployment of these new clean stoves/fuels usually starts from a pilot program, and at present, most programs are initially financed through the carbon market (Aung et al., 2016). It was reported that of 8.2 million improved stoves distributed in 2012 and tracked by the Global Alliance for Clean Cookstoves (GACC), half received carbon financing through the Clean Development Mechanism (CDM) (Putti et al., 2015). Recently, a study in India found that the replacement of traditional wood stoves by improved wood stoves did not significantly reduce wood consumption, and moreover, there was a higher proportion of light-absorbing black carbon in $PM_{2.5}$ from the intervention compared with traditional stoves (Aung et al., 2016). The study indicated that in the absence of field-based evaluations, the intervention program may fail to achieve the intended carbon reductions and co-benefits to health (Aung et al., 2016).

In China, the National Improved Stove Program (NISP) during the 1980s and 1990s introduced over 100 million improved stoves to replace traditional ones (Smith et al., 1993; World Bank, 2013). Through that program, many stoves were improved by adding a chimney and/or grate, and by optimizing the stove chamber design. During the last three decades, cookstove technologies and markets in China have developed quickly, and some novel technologies such as biomass gasifier stoves and forced-draft cookstoves have been used in some regions (Shen et al., 2015a). Besides some projects initiated and supported by the central and local governments (World Bank, 2013), many clean stove and fuel intervention programs in China are also conducted through CDM (Chen et al., 2010; Global Alliance for Clean Cookstoves; Zhang, 2012). Field testing is essential to evaluate the performance of these clean stoves/fuels, however, such measurements are still very limited at this stage.

In Enshi County, Hubei, China, coal stoves with chimneys are widely used for daily cooking and heating. Starting in 2012, wood-gasifier stoves (ZQ-JG-220, Enshi Biomass Energy Development Co., China) were deployed to replace traditional coal stoves in this area to reduce carbon emissions (Zhang, 2012). Approximately 80,000 wood-gasifier stoves have been deployed in the area. This new generation of improved stoves usually has higher thermal efficiency with fuel savings and air pollutant emission reductions in previous laboratory tests (Chen et al., 2016a; Shen et al., 2012a; Jetter et al., 2012; Kshirsagar and Kalamkar, 2014). However, laboratory tests have been found to be unable to simulate some high emissions episodes, and to capture large variations in emissions (Chen et al., 2016a; Shen et al., 2015b). Therefore, field evaluation becomes critical for a better understanding of stove performance. A previous emission test was performed in 2012 to characterize and compare air pollutant emissions from coal and wood combustions (Shen et al., 2015b). In January 2014, two years after the first measurement, we conducted a second field campaign in Enshi, with main focuses on 1) characterization of fuel consumption and air pollutant emissions from the wood gasifier stoves following a two-year usage period; 2) potential impacts of residential emissions on climate when replacing coal stoves by wood gasifier stoves in the pilot area; and 3) household air pollution in homes using coal and wood stoves.

2. Method

2.1. Field site and kitchen performance test

Field measurements were conducted in Enshi County, China in January 2014. Kitchen Performance Test (KPT) was performed over an extended period of 3 days to quantify the daily fuel use (Bailis et al., 2007). Sufficient fuels for 3 days were prepared and pre-weighed using an electric balance with a precision of 20 g. The test team revisited those households after three days to weigh the remaining fuels. A total of 144 homes, of which 72 were using wood and 72 were using coal, participated in the KPT test.

In the studied area, both coal and wood gasifier stoves are designed to provide space heating through radiant heats, besides cooking use. The space heating practices in the south China region are different from that in the north China, where central heating is popular and usually all rooms are heated in both day and night time. In south area, space heating is often from the radiant heats from wood or coal burning in home stoves, especially in rural area where the use of gas or electricity for heating is not affordable. Local residents are used to sit around the stove in kitchen for heating demands. During non-cooking periods, typically, a pot of water was boiled to keep fuel burning in the stove chamber and to provide radiant heating. Consequently, fuel consumption amount from the KPT is the total fuel consumption, and which consumption for cooking and heating cannot be estimated separately.

2.2. Field emission measurements

The emission measurements were performed in fifteen randomly selected households, of which 8 had adopted wood gasifier stoves and 7 were still using coal stoves. Emissions sampling was conducted during lunch time and the residents were asked to cook and operate the stoves as they did in daily lives. Emission sampling lasted for 40 min starting from fire ignition to stable burning period (Chen et al., 2016a,b). Pictures of the stoves and fuels are provided in Supporting Information (Fig. S1). Emissions were sampled from the outlets of the stove chimneys. A proportion of the fuel was taken back to the laboratory for elemental and proximate analysis. The fuel analysis result is listed in the Appendix (Table S1).

The sample probe was placed near the center of each chimney. No further dilution was performed during this field sampling campaign. Gaseous CO and CO_2 were measured using a nondispersive infrared sensor (GXH-3051, Technical Institute, Beijing, China), and the NOx and SO_2 were measured by electrochemical and infrared sensors, respectively (JFQ-3150E, Technical Institute, Beijing, China). The equipment was calibrated using a span gas in the laboratory prior to use in the field, and it was zero-checked before each field sampling cycle. The total suspended particles (TSP) were collected on quartz fiber filters (QFFs, 24 mm in diameter) and used for OC/EC analysis. PM_{10} and $PM_{2.5}$ samples were collected on glass fiber filters (GFFs, 37 mm in diameters) using active impaction samplers (SKC, Eighty Four, PA, USA). Two parallel samples were collected for both PM_{10} and $PM_{2.5}$ in each test. The pump flow rate was ~2.0 L/min. The pump was calibrated before and after each sampling cycle using a primary flow calibrator (Bios Defender 510, USA). All filters were baked at 450 °C for 6 h and equilibrated in a desiccator in the laboratory. The filters were packed and sealed separately in clean aluminum foil bags before and after each sampling cycle. All samples were stored in a refrigerator at a temperature of -20 °C prior to lab analysis. The field measurements were completed within a week, thus, the weather and fuel humidity conditions were expected to be similar during different test cycles.