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Comparative performance of five Mexican plancha-type cookstoves using water boiling tests

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ABSTRACT

While plancha-type cookstoves are very popular and widely disseminated in Latin America, few peer review articles exist documenting their detailed technical performance. In this paper we use the standard Water Boiling Tests (WBT) to assess the energy and emission performance of five plancha-type cookstoves disseminated in about 450 thousand Mexican rural homes compared to the traditional 3-stone fire (TSF). In the high-power phase, average modified combustion efficiencies (MCE) for plancha-type stoves were 97 ± 1% which was higher than TSF 93 ± 4%, and reductions in CO and $PM_{2.5}$ total emissions were on average 44%. Time to boil and specific fuel consumption, however, were increased in plancha-type stoves compared to the open fire as a result of the reduced overall thermal efficiency of the plancha during WBT. In the simmering phase, plancha-type stoves showed much more consistent performance reductions compared to the TSF. MCE for plancha stoves were on average 98 ± 1% and 95 ± 3% for the TSF, while reductions in CO and $PM_{2.5}$ total emissions were on average 55%. In this phase 27% average savings in fuel use are achieved by plancha-type stoves. Removal of the plancha rings resulted in savings of specific fuel consumption (SFC), thermal efficiency (TE), and time to boil; however, CO and $PM_{2.5}$ emissions increased significantly as flue air is drawn through the comal surface rather than through the combustion zone, resulting in suboptimal combustion conditions.

International Workshop Agreement (IWA) energy performance Tiers for plancha-type stoves ranged from 0 to 1. However, these results contrast sharply with the well documented reductions in fuel consumption during daily cooking activities achieved by these stoves. IWA indoor emissions Tiers are 4 for both $PM_{2.5}$ and CO using locally measured values for fugitive emissions. Optimization of combustion chamber design on these stoves in Mexico is desirable to further reduce indoor emissions and to reduce the impacts of neighborhood pollution that can re-infiltrate kitchens. Comparison of performance between plancha-type stoves and unvented stoves should reflect the substantial gains that are made by reducing indoor air pollution and exposures by venting pollutants.

1. Introduction

Plancha-type cookstoves have been widely disseminated in Mexico as they are well suited to local cooking customs and are widely accepted in local communities [1]. Between 2007 and 2012 a total of more than 600,000 plancha-type stoves had been disseminated, mostly through the *Programa Nacional de Estufas de Leña* [2]. Recently, assessment of cookstoves technical performance has been integrated into a standardized guidance through an International Workshop Agreement (IWA) 11:2012 of the International Standards Organization [3], that provide performance Tiers of efficiency, emissions and safety [4]. Although there is a standard for total emissions, ISO standards to protect health largely address open combustion type stoves, and stoves without flues. There is a clear exposure benefit that

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well-functioning chimney stoves provide as only a fraction of the emissions enter the kitchen via fugitive emissions and re-infiltration. The World Health Organization (WHO) Indoor Air Quality Guidelines present emission rates for both vented and unvented stoves, where the emission rate for vented stoves used a normal distribution for the fraction of emissions entering the kitchen, ranging from 1 to 50% with a mean of 25% and standard deviation of 10% of the emissions from an unvented stove [5]. The IWA standards were established with Tiers for indoor emissions, which represent fugitive emissions for a stove with a flue, and total emissions based on reductions in emissions rates in a transition from open fires to modern forced draft stoves. Cognizant of the gaps in information for specific stove, IWA workshops recommended that new protocols be developed or current protocols be updated to more adequately address a larger number of stove and fuel types, such as heating stoves, plancha stoves, charcoal stoves, double pot stoves and solar cookers [6].

In this paper we examine the energy and emission performance of 5 Mexican plancha-type stoves in comparison with a 3-stone fire (TSF) using standard Water Boiling Tests (WBT). We highlight the issues involved in incorporating plancha-type stoves into IWA guidance. We examine the reasons for poor performance of plancha-type stoves in WBT in relation to actual performance during daily cooking tasks in real homes, and suggest some modifications to test protocols to better reflect the actual performance of these stoves. These suggestions can be useful for IWA current activities on adapting the WBT for plancha stoves.

2. Methods

2.1. Stoves distribution

Fig. 1 shows the 5 plancha-type stoves tested: Patsari, Patsari Portatil, ONIL, Mera-Mera, and Ecostufa. Distribution of the Patsari has been approximately 200,000 in several Mexican States such as Michoacan, Oaxaca, Sinaloa, and others. Distribution of the ONIL has been approximately 90,000 predominantly in Guerrero, Oaxaca, San Luis Potosí, and Chiapas. The extent of Mera-Mera and Ecostufa distribution is not known precisely, but several thousands have also been distributed in different Mexican States. The total estimated distribution is more than 450 thousand stoves installed in the field. The Patsari stove is built in-situ and the rest are mass-produced. The ONIL and Mera-Mera have metallic rings insert in the plancha surface that can be removed to improve the heat transfer pot to comal[5] (see Supplementary section for more detailed information about each stove tested). The ONIL and ONIL without rings were evaluated to highlight the impact of the plancha surface in changing emission and performance metrics as can be seen in Fig. 2.

2.2. Water boiling test

The WBT protocol version 4.1.2 [7] was used to determine performance and emission parameters of the plancha-type stoves and the TSF. All plancha-type stoves were started with a small amount (~30 g) of "ocote" that is a highly resinous piece of pitch pine. For all three phases of the WBT protocol, a digital scale with 1 g resolution was used to determinate measurements of the mass of fuel used. White oak (*Quercus bicolor*) was used in all WBT test, and the average dimensions of fuel were 2 cm×4 cm×40 cm. Fuel moisture was determined by a Protimeter Timbermaster Wood Moisture Meter, and nine measurements for each test for each stove were made [8]. The average fuelwood moisture content for all tests was 8.8 ± 1.4% on a wet basis with a range of 7–13%.

[5] Comal is a flat metal surface lying immediately over the combustion zone on which food items and pots to cook food are placed.

Fig. 1. Stoves tested. Left to right: Ecostufa, Mera-Mera, Patsari Portatil, 3-stone fire, ONIL and Patsari.

2.3. Emission measurements

Emission measurements were made using a Portable Emissions Measurement System (PEMS) (Aprovecho Research Center, Oregon USA), consisting of a hood under constant flow which collects emissions from the cookstove being tested. Real-time concentrations are measured using a NDIR (non-dispersive infrared) sensor for CO_2, an electrochemical cell to measure CO, and a light scattering photometer to estimate $PM_{2.5}$. CO_2 and CO sensors were calibrated using zero air and a mixture of 100 ppm CO and 3000 ppm CO_2 [9]. Constant flow hoods have been used previously to capture and measure emissions from cookstoves in laboratory or simulated kitchen settings [10–13].

Light scattering by particles is dependent on the scattering coefficient of particles, mass scattering cross section and the particle size distribution [14], PEM $PM_{2.5}$ light scattering measurements were referenced to simultaneously collected gravimetric filter based measurements from in-lab testing using the same stove and wood type by the following adjustment factors:

$$\text{Patsari}: (y\,[PM_{2.5,\text{filter}}]=5.1\,[PM_{2.5,\text{optical}}]+5417),\ R^2=0.84, \tag{1}$$

$$\text{Ecostufa}: (y\,[PM_{2.5,\text{filter}}]=19\,[PM_{2.5,\text{optical}}]+2690),\ R^2=0.90, \tag{2}$$

$$\text{ONIL}: (y\,[PM_{2.5,\text{filter}}]=11\,[PM_{2.5,\text{optical}}]+2667),\ R^2=0.99, \tag{3}$$

where $[PM_{2.5,\text{filter}}]$ and $[PM_{2.5,\text{optical}}]$ are filter and optical $PM_{2.5}$ concentration, respectively. Eq. (1) was used to adjust Patsari Portatil and Mera-Mera $PM_{2.5}$ light scattering concentrations as filter data were not available for these measurements.

2.4. Data analysis

When the number of replicates is small, the t-test is recommended over ranked transformations and the Welch test [15]. Statistical analysis of difference in means was done using a two sample t-test, and probability of error of $p \leq 0.05$ was considered statistically significant as reported by Grimsby et al. [16] and Berrueta et al. [17], respectively. Coefficient of variation (CV) and t-distribution for plancha-type stoves performance during WBT phases are shown in Appendix A, Table A1. The 95% confidence interval (CI) indicates the reliability of the means based on the number of test replicates, where the true mean has 95% chance of lying within the confidence interval. Emissions reductions and 95% CI from plancha-type stoves relative to TSF are shown in Table A2.