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Laboratory experiments regarding the use of filtration and retained heat to reduce particulate matter emissions from biomass cooking

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ABSTRACT

There are a number of methods to help reduce the exposure to household air pollution associated with using biomass fuel for daily cooking and heating in nearly 40% of global households. These most commonly include use of cleaner fuels and cookstoves, increasing ventilation, and use of a chimney. This paper investigates two less-commonly considered methods, 1) reducing exposure through filtration and capture of $PM_{2.5}$ and 2) avoiding emissions using retained heat for cooking. If cookstoves are operated inside an enclosure from which smoke is pulled by a fan through an inexpensive HEPA-type filter before exiting to the outside, the personal exposure levels, room concentrations, and external pollution might be reduced. To test this method, an enclosure was built from which a box fan pulled the air and $PM_{2.5}$ through a filter, and four different filters were tested. The rate of $PM_{2.5}$ production (mg/min) exiting the filter was monitored with gravimetric measurement under an emissions hood during the high and low power phases of the Water Boiling Test 4.2.3 conducted on a biomass rocket stove with forced draft. The average of seven baseline emissions tests with no filter was 7.5 mg/min of $PM_{2.5}$. The average of seven tests using the highest quality furnace filter (3 M 2200) was reduced to 1.5 mg/min and the difference was significant at 95% confidence. The use of retained heat to simmer also reduced emissions of $PM_{2.5}$ to zero by burning the boil-phase-made-charcoal while 5 l of water were simmered for 35 min.

Introduction

Household air pollution produced by cooking and heating in the homes of nearly 40% of the world's population is responsible for an estimated 4.3 million premature deaths per year, and approximately 25% of black carbon emissions are caused by wood fires used mostly for cooking food by nearly 2.7 billion people worldwide (Bond et al., 2013; WHO, 2014). Exposure to higher concentrations of PM2.5 causes asthma, respiratory inflammation, pneumonia, jeopardizes lung functions, promotes cancers and represents the 2nd leading cause of death for women worldwide and the leading cause of death for children under 5. Significant lost productivity and other opportunity costs are involved, as well (Lim, Theo, Flaxman, Danaei, & Shibuya, 2012). Despite ongoing international efforts for electrification and other clean energy infrastructure, the use of biomass for cooking is projected to continue to be the dominant energy source for rural, low income households through 2030 (Daioglou, van Ruijven, & van Vuuren, 2012). The preliminary research presented here seeks to investigate a novel method for reducing this exposure through post combustion filtration, and to remind the community of the avoided emissions that are a result of retained heat cooking.

Fine particulate matter, or $PM_{2.5}$, is of primary concern to health as the particles 2.5 μm or smaller travel past nasal passages and penetrate deep into the lungs (WHO, 2013). In order to protect health, global organizations are working to reduce household exposure to $PM_{2.5}$ to levels deemed safe by the World Health Organization (WHO). Interim Air Quality Guideline (AQG) targets are currently set at 35 $\mu g/m^3$ for an annual mean concentration with an ultimate goal of 10 $\mu g/m^3$ (WHO, 2014). However, today concentrations in many rural homes around the world are orders of magnitude higher than these targets (Lim et al., 2012; Smith et al., 2014). There are a number of methods that can help to reduce exposure to the indoor air pollution, particularly for $PM_{2.5}$. These include

1. Switching to cleaner-burning fuels such as LPG
2. Improving thermal efficiency so less wood is burned per task
3. Utilizing biomass cookstoves with improved combustion efficiency such as gasifier stoves and forced draft cookstoves
4. Using a chimney to vent emissions outside
5. Increasing ventilation or cooking outside

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6. Capturing particles in a filter
7. Avoiding particulate production by simmering using retained heat

The continued use of traditional stoves along with improved stoves (stove stacking) and the challenges of achieving extremely clean combustion may indicate that the intervention of clean stoves and fuels alone may not be enough to reach WHO goals. The 100% replacement of traditional biomass stoves by newly-introduced cleaner fuel stoves or cleaner burning biomass stoves only rarely occurs (Masera, Díaz, & Berrueta, 2005; Ruiz-Mercado & Masera, 2015). For example, cooking with LPG has been accompanied by a continued use of the open fire resulting in only a 45% reduction in $PM_{2.5}$ in kitchens in Guatemala (Albalak, Bruce, McCracken, Smith, & de Gallardo, 2001). In the same study, a griddle stove with chimney emitted approximately 15% of the emissions into the kitchen air. A study of a griddle stove, the Patsari, resulted in a 74% reduction in median 48 h $PM_{2.5}$ concentrations in kitchens and a 35% reduction in median 24 h personal exposures due to various other sources of emissions (Cynthia et al., 2008). A recent study in India found that 40% of families continued to use the traditional stove alongside of the improved stove. When the improved Rocket stove was used exclusively, the measured levels of $PM_{2.5}$ were reduced from the baseline seasonal increase of 139 $\mu g/m^3$ to a seasonal increase of 51 $\mu g/m^3$. However, when the traditional and improved stoves were both used the average level of $PM_{2.5}$ seasonal increase rose to 92 $\mu g/m^3$ (Aung et al., 2016). Perhaps filtration of $PM_{2.5}$ before exiting the stove could address both interior and exterior levels of harmful concentrations.

Adding a chimney to the stove, increasing the air exchange rate inside the kitchen, or even cooking outside under a veranda are interventions that can help but can still result in unhealthy exposures, especially in locales where the external air already exceeds safe concentrations as in many urban environments (WHO, 2005). Smoke hoods have been installed in Nepal that can accommodate different stoves while diverting smoke up a chimney (Bates, 2007). Chimneys reduced the interior concentrations of $PM_{2.5}$ by about 90% in a study in Kenya (Majdan, Svaro, Kralova, Muendo, & Taylor, 2015). Opening the window and door in a test kitchen lowered concentrations of $PM_{2.5}$ by about 93% in a study of biomass stoves, but conditions still did not meet the WHO indoor air $PM_{2.5}$ guidelines for protecting health (Grabow, Still, & Bentson, 2013).

Other potential methods to reduce exposure that have not commonly been addressed for cookstoves are the use of filters to collect and sequester the particles, and the use of retained heat to increase efficiency and avoid emissions altogether. The effectiveness of these methods in reducing $PM_{2.5}$ and CO emissions is evaluated here.

Background

Air quality guidelines

The World Health Organization recently published intermediate and ultimate emission rate target indoor air guidelines for vented and unvented cookstoves (WHO, 2014). Their strong recommendation was to direct governments and implementers to advocate technologies and fuels that are proven to protect health. The International Organization for Standardization (ISO) International Workshop Agreement (IWA) has also set tier-based targets for emission rates (ISO, 2012). The maximum air pollutant emission rates for cookstoves in actual use both in the interim and the ultimate targets recommended by the WHO are shown in Table 1. These levels were derived by calculating the effect of emissions using a box model that estimated room concentrations based on distributions of room size, air exchange rate, cooking time, and the efficiency of the chimney (at removing emissions from the kitchen) as found in homes in which biomass is used for cooking.

Advances in the combustion efficiency in biomass cook stoves are approaching, but do not comfortably meet, the new WHO and ISO/IWA emission rate targets. In a Water Boiling Test (GACC, 2014) survey of 22 biomass stoves, the lowest $PM_{2.5}$ emissions (on the basis of useful energy delivered to the cook pot) were 74 mg/MJ_d (approximately 8 mg/min) compared with 700–1400 mg/MJ_d (approximately 50 mg/min to 100 mg/min) from the baseline open fire (Jetter et al., 2012). In another survey of advanced cookstoves reporting the average of three Water Boiling Tests in the laboratory, eight of fifteen biomass stoves met the WHO Emission Rate Target for CO by emitting <0.16 g/min (Still, Bentson, and Li, 2015). In the same study, seven biomass stoves met the Intermediate $PM_{2.5}$ Emission Rate Target for vented stoves by emitting <7.15 mg/min. Although not all of the stoves were actually vented the fact that they met the emissions rate target illustrates how the combustion technology is present to protect health. None of the fifteen advanced cooking stoves met the intermediate unvented stove $PM_{2.5}$ standard of <1.75 mg/min. At this point in time, the cleanest burning biomass stoves seem to emit approximately 3 to 4 mg/min PM2.5 when carefully operated in a laboratory (Still, Bentson, Lawrence, and Andreatta, 2015). Between 2014 and 2016, the US Department of Energy has supported fairly extensive research and development of a new generation of biomass cook stoves that are currently undergoing testing at the Lawrence Berkeley National Laboratory.

Although the emission rates from new biomass stoves are being reduced, they do not yet meet the targets in laboratory testing and in-use performance in the field is expected to be worse. In addition, the continued use of traditional stoves through stove stacking to meet needs for different cooking and other energy tasks can decrease the positive effects of cooking with even very clean burning stoves and fuels like LPG.

Table 1
WHO Guidelines (WHO, 2014) and ISO IWA performance tiers (ISO, 2012).

	WHO intermediate	WHO Ultimate	ISO IWA
Unvented stove[a]			
$PM_{2.5}$ (mg/min)	1.75	0.23	Tier 1 < 40
			Tier 2 < 17
			Tier 3 < 8
			Tier 4 < 2
Vented Stove[a]			Fugitive emissions
$PM_{2.5}$ (mg/min)	7.15	0.80	Tier 1 < 40
			Tier 2 < 17
			Tier 3 < 8
			Tier 4 < 2

[a] The WHO Guidelines account for total emissions from both vented and unvented stoves. The ISO/IWA vented stove metrics are measures of fugitive emissions into the room.

Filtration

The reduction of emissions of $PM_{2.5}$ from industrial sources often depends on both improved combustion efficiency and the post-combustion filtration/scrubbing of emissions by various techniques. Technologies used on larger wood fired boilers include Mechanical Collectors (cyclones), Fabric Filters (bag houses), and Electrostatic Precipitators (ESPs). Of these methods, fabric filters are most appropriate to household combustion applications because they do not require complicated or expensive equipment. Fabric filters trap particulates before they exit the chimney and can capture up to 99.9% of the mass of total particulate emissions. There are several types of fabric filters and various ways of cleaning the filters such as mechanical and pulse jet cleaning. Industrial fabric filters can be relatively inexpensive. For example, a 12.75″ diameter by 26″ length cartridge with 226 ft^2 of wrapped polyester/cellulose filter media was $60 (Turner and The EPA, 1998). While some fabric filters can be renewed periodically by cleaning, common household furnace filters are discarded after a significant loading of deposited particulate. Household filters are typically made of matted fibers, mounted in frames, and used where particulate matter concentrations are relatively low. Industrial fabric filters are