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Extended Abstract #1

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INTRODUCTION

Half of the world's population cooks domestically with simple biomass stoves.[1] This intensive use of biomass as cooking fuel is associated with severe health-related and environmental problems. Wood smoke contributes nearly 3% to the total global burden of disease, resulting in 1.6 million premature deaths annually, including 900 thousand children under the age of five.[2] Biomass combustion can also contribute to atmospheric visibility degradation, deforestation, soil erosion, and global warming. There have been a number of studies to evaluate impacts of cookstove emissions on health and climate.[3,4,5] However, the effect of biomass cookstove use on atmospheric visibility has been rarely reported in the current literature.

Light traveling through the atmosphere can be absorbed and scattered by particles and gas molecules. Light scattering (σ_{scat}) and absorption (σ_{aba}), collectively known as light extinction ($\sigma_{ext} = \sigma_{scat} + \sigma_{aba}$), remove light from a beam and thus lead to a decreased visible range. Atmospheric particles are the main contributors to extinction in most visibility impaired areas.[6] Most of the particles from biomass combustion contain black carbon (absorb light) and organic carbon (scatter light). Several prior studies have measured light absorption and light scattering properties of biomass cookstove particles.[7,8] However, those optical properties data were merely analyzed for the climatic impact estimation.

This study quantifies light scattering and absorption properties of particulate matter (PM) emitted from Berkeley-Darfur Stove (BDS) and traditional Three Stone Fire (TSF) by conducting laboratory tests. The impact of BDS and TSF emissions on visibility are compared based on the light extinction coefficient. The climate impact of switching from TSF to BDS is reported in a companion paper.[9] It is anticipated that the information generated in this study will aid in improving atmospheric visibility by replacing traditional cookstoves with improved cookstoves. The major limitation of this study is that current laboratory experiments are not representative of the actual everyday cooking practices. Biomass cooking emissions highly depend on fuel type, heat required by different food types, and the cook's skill and attention level. Future work needs to be focused on in-field stove emission characterization.

EXPERIMENTAL METHODS

This study was performed at the Lawrence Berkeley National Laboratory cookstove testing facility. Cooking was carried out on a platform underneath a hood. A blower connected to the hood via an aluminum duct (D = 15 cm) drew the smoke from cooking fires and room air into the hood. The smoke and room air mixed along the length of the duct, aided by stationary fan blades, turns in the duct, and turbulent flow. At a point prior to the blower, diluted smoke was

drawn via stainless steel tubing (D = 1.1 cm) through a Very Sharp Cut Cyclone (BGI, model VSCC) to remove particles with D_p larger than 2.5 μm.[10] Downstream of the cyclone, the sample flow was split using two-way stainless steel flow splitters (BMI, models 1100 − 1102) and sampled with various instruments. Dry, particle-free air was mixed with a portion of the flow to further dilute the particulate matter concentration by about a factor of 10 prior to sampling.

CO and CO_2 were measured in a single instrument by nondispersive infrared absorption spectroscopy. $PM_{2.5}$ and BC were measured using a DustTrak and aethalometer, respectively. Absorption and scattering coefficients at a wavelength of 532 nm were measured using a custom-made instrument employing photoacoustic absorption and reciprocal nephelometry. [11,12] This instrument measures the sound produced when particles heated with a 532 nm laser in an acoustic resonator transfer heat to the surrounding air. From this measurement and the laser power, aerosol light absorption is calculated.[11] The instrument simultaneously measures scattering coefficient at the same wavelength in a separate cell employing the principle of reciprocal nephelometry.[12] Airflow into the instrument is split between the photoacoustic and nephelometer cells and flows into these cells are set so that the time constant of each cell is similar. The calibration of this instrument was verified using ammonium sulfate and soot particulate matter prior to this study.[13] The relative humidity measured inside the photoacoustic instrument was typically 10%. This is sufficiently dry to result in efflorescence, so the sampled particulate matter is presumed to be dry. Thus, the photoacoustic measurement was not likely affected by the evaporation of water from particle surfaces and the scattering of light by particles was not enhanced by water-increased particle cross-section.

The BDS and TSF are compared in this study using the same cooking test, which featured the boiling of water. The pictures of BDS and TSF are shown in Figure 1. Like other water boiling tests intended to mimic cooking food, this test is intended to simulate the cooking of Assida, a common food in Darfur. In this test, a wood fire was ignited by burning one sheet of crumpled newspaper, and 2.5 L of water in a 2.3 kg metal Darfur pot was heated from an average temperature of 21 ± 4 °C to 100°C. The temperature of the water was recorded using a digital thermometer equipped with a type K thermocouple. After the water began to boil, a flaming fire was maintained and the water temperature was not permitted to drop below 94 °C for 15 minutes. After this 15 minute period, the fire was extinguished so that the remaining mass of wood could be measured. This test, therefore, does not capture pollutant emissions under exclusively smoldering conditions that occur when flames extinguish.

Figure 1. Pictures of the three stone fire (left) and the Berkeley-Darfur Stove (right).

Soft (pine and fir) and hard (oak) woods were used in an equal number of tests with both stove types. Soft wood pieces were saw-cut to approximately 15 cm long with a square cross-section of approximately 4 cm^2 and hard wood pieces were hatchet-cut to a similar size but irregular shape. The moisture content and dry mass of the soft and hard woods were similar to each other and were the same for TSF and BDS tests. The moisture content of soft wood (9 ± 2 %) and hard wood (10 ± 2 %) pieces was essentially the same. The dry mass of soft (20 ± 9 g) and hard wood (26 ± 13 g) pieces was similar. The data presented below are the result of 21 tests with the BDS and 20 tests with the TSF. An equal number of prior tests were conducted to optimize and develop consistency in sampling, measurement, and cooking methods. In general, all instrumentation discussed above properly operated during these 41 tests.

RESULTS & DISCUSSION

Figure 2 shows the statistics of the light absorption, scattering and extinction coefficients of the smoke emitted from BDS and TSF. BDS data showed a larger degree of test-to-test variability compared to the TSF, and the distributions of absorption, scattering and extinction with BDS and TSF overlapped completely. Compared to the TSF, the arithmetic average absorption coefficient of BDS is higher, while the arithmetic average scattering coefficient of BDS is lower, which indicates that PM emissions of the BDS were, on the whole, more light absorbing (blacker). The arithmetic average of the light extinction coefficient of BDS and TSF is nearly the same. However, there is no significant difference of the median value between BDS and TSF for all the three optical properties (Mann-Whitney test, $p > 0.1$).
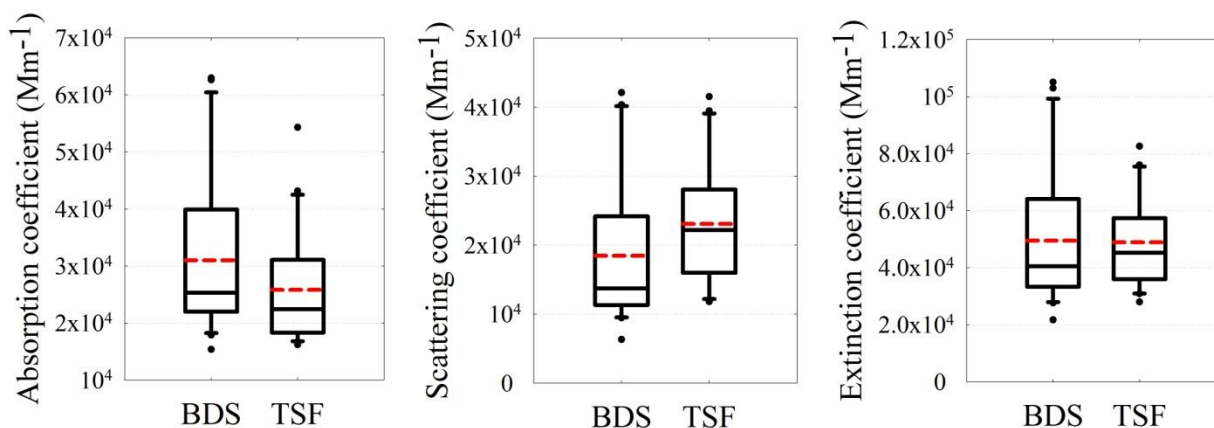

Figure 2. Box plots showing the light absorption, scattering and extinction coefficients of the BDS and TSF smoke. Box-whisker plot indicates median and 25/75% quartile (boxes), mean (red dash line), 10/90% quartiles (whiskers), and 5/95% quartiles (dots).

Figure 3 illustrates the typical light extinction coefficient values for various PM sources. It is well known that sand storm, vehicular emissions, volcano plume, oil/forest fires all largely contribute to visibility impairment.[14-18] The light extinction coefficient values for BDS and TSF measured in this study are both substantially greater compared to the above mentioned sources. Similar results were found in a field study, which characterized real-time optical properties of PM emitted from traditional Honduran cookstoves.[7] However, field measurements of cooktove PM emissions can be over three times as large as laboratory measured emissions using the same

sampling methodology.[8] In our laboratory tests, stable ambient conditions, use of consistent fuel and careful stove operation lead to less emission variability.
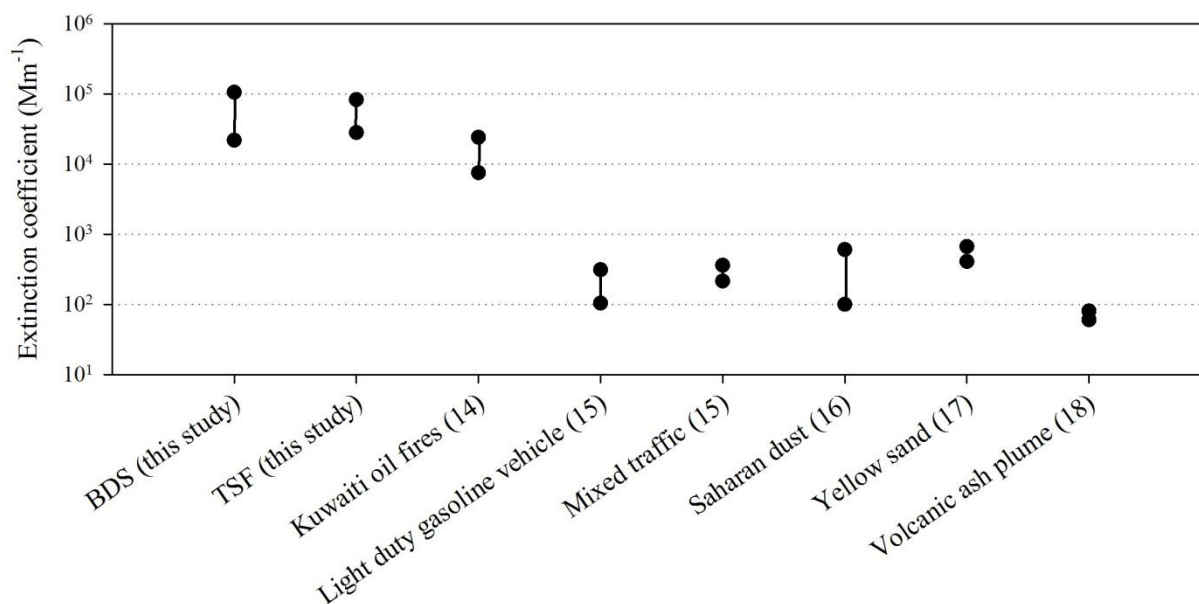

Figure 3. Comparison of the light extinction coefficient for particles emitted from various sources. Lower and upper dots represent minimum and maximum values, respectively.

SUMMARY

- The absorption of BDS PM contributes more to the extinction (63%) compared to scattering. The scattering and absorption of TSF smoke are nearly the same (48% vs. 52%). On the whole, the BDS smoke is blacker than the TSF smoke.
- The arithmetic average light extinction coefficients of BDS and TSF smoke are similar and comparable with those reported in prior biomass cookstove emission studies. The median values are of no significant difference between BDS and TSF.
- The light extinction coefficients of both BDS and TSF are substantially higher compared to other common PM sources, which can dramatically impair the atmospheric visibility.
- The large-scale replacement of the TSF with the BDS probably cannot improve the atmospheric visibility based on these laboratory emission tests.
- Our laboratory test result should not be considered to be representative of in-use biomass cookstove emissions in the real world. To promote a deeper and more accurate understanding of particle optical properties of in-field stoves, field tests are indispensible and laboratory tests need to be redesigned to emulate the critical variables governing emissions.

ACKNOWLEDGMENTS

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KEYWORDS

Cookstove, Visibility, Light extinction, Particulate matter, Berkeley-Darfur Stove (BDS)