In-situ Measurements of Soot Production in the Berkeley-Darfur Stove using Laser Extinction

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Worldwide, approximately three billion people cook their food using biomass fuels such as wood, charcoal, crop residues, and animal dung. The emissions produced by these smoky fires lead to four million premature deaths annually and large environmental consequences. While the negative effects of biomass burning have spurred much research into designing less polluting cookstoves, researchers need a knowledge-base to draw from when making design decisions. However, previous research has measured these emissions relatively far away from the source, not exploring how the design modifications affect the actual combustion. In this study, the emissions from an improved cookstove, the Berkeley-Darfur Stove, and single blocks of wood are examined in-situ using laser extinction. The pollutant production, measured by the opacity or soot volume fraction, was compared between the two systems to gain a deeper understanding of combustion in the stove while providing initial steps towards a non-intrusive sampling system for pollutant production in cookstove combustion chambers.

1. Introduction

Smoke from current biomass cooking stoves used by three billion people around the world leads to enormous health and environmental issues. This smoke is associated with 4 million deaths per year due to adverse impacts on respiratory, cardiovascular, neonatal, and cancerous conditions, and was recently determined to be the largest environmental threat to health in the world [1, 2]. Biomass cooking has also been found to significantly contribute to global climate change, including promoting increased snow and ice melt [3, 4].

Due to the undesirable side effects caused by current cooking practices, there is considerable interest in developing fuel-efficient biomass stoves with hundreds of researchers around the world striving to reduce pollutant emissions [5]. However, few of those researchers are specifically studying the combustion occurring in the stove; instead, the focus is on emissions that have left the stove. Emission measurements provide a useful overall emission profile for the stove, however only non-intrusive diagnostic techniques that probe the combustion chamber can provide the flame characteristics on a local level so that the regions of the stove to be modified for emissions reduction will be known instead of hypothesized.

Applying modern combustion diagnostic techniques, similar to those used for engines and power plants, to cookstoves will provide insight about the characteristics of combustion in stoves that have previously gone unmeasured.

2. Laser Methodology and Experimental Arrangement

Laser extinction was chosen as the measurement technique for this system as it is well-known, adaptable, nonintrusive, and robust, even being used as a calibration technique for other methods [6, 7]. It is a line-of-sight technique that measures the attenuation of the laser beam, that is, how much of the laser light is attenuated by particulates in the beam-path, as it passes through the flame. The simplicity of the optics needed allows for more flexibility in experimentation as only requiring one laser to go through the fire lessens the number of optical entry points needed into the stove.

The experimental arrangement is shown in Fig. 1. A 1064 nm continuous wave laser was used with a frequency controlled chopper fixed at 170 Hz to provide laser pulses. The 1064 nm wavelength laser was chosen to avoid some well documented issues with PAH absorption created when using a laser in the visible spectrum [8].

A 500 mm plano-convex spherical lens was used to provide partial reflection of the laser beam. This reflected beam was aligned to a photodiode to provide baseline data to account for laser power fluctuations. The transmitted beam passed through the region of interest into a second photodiode to measure the beam attenuation.

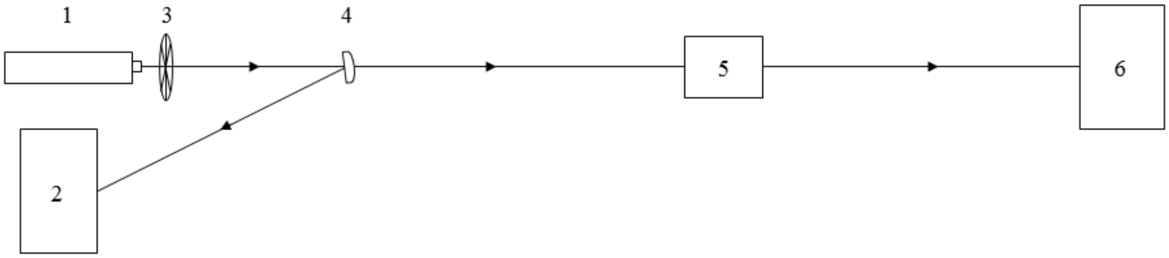

Figure 1: Experimental arrangement of optics. From left to right: (1) 1064 nm Nd:YAG laser; (2) Reflected laser photodiode; (3) Chopper; (4) Plano-convex spherical lens; (5) Combustion zone; and (6) Transmitted laser photodiode.

The amount of particulate matter in the measurement volume is inferred by the attenuation of the beam, which is found using the ratio of the signals of the transmitted and reflected laser light. The chopper produces periodic blockages of the laser beam, thereby providing an indication of the background signal received at each photodiode, necessary to correct the signal for extraneous light detection.

The total signal attenuation can be calculated from the following equation:

$$\frac{I}{I_o} = \frac{I_T - I_{T,o}}{(I_R - I_{R,o}) \times C} \tag{1}$$

where I is the transmitted intensity and I_o is the incident intensity. I_T is the transmitted signal intensity and I_R is the reflected signal intensity recorded at the photodiodes. $I_{T,o}$ and $I_{R,o}$ are the background signal portions produced by the chopper for the transmitted and reflected signal, respectively. C is a correctional constant for background noise; it is derived from the total signal attenuation for the experimental setup without a flame, recorded before and after each test.

The soot volume fraction, which in the case of a wood flame is not just related to soot but all opaque portions of smoke, is calculated using the Bouger-Lambert-Beer Law:

$$\frac{I}{I_o} = e^{\frac{-K_e f_v L}{\lambda}} \tag{2}$$

where I and I_o are defined in Eq. (1), K_e is the light extinction coefficient, f_v is the soot volume fraction, λ is the laser wavelength, and L is the optical path length through the flame [6].

The light extinction coefficient K_e is an experimentally determined value that is fuel and laser wavelength dependent. From the work done by Choi *et al.*, the K_e value was chosen to be 9 although this is likely to be an overestimation due to the differences in laser wavelengths between that work and the current experiment (633 nm vs. 1064 nm) [6].

3. Wood block trials

Solid fuel systems are quite difficult to analyze due to the non-homogeneity of the system, so it was useful to obtain example burn profiles of a relatively well-defined system. As a simplified trial, the combustion of individual 20 mm cubes of locally-sourced Australian Douglas fir was explored.

3.a Experimental Setup & Protocol

Each wood block was combusted using a continuous natural gas flame located 45 mm below the center of the block. The grain of the wood was parallel to the laser, which was aligned along the centerline of the wood block, 10 mm above the surface of the wood block.

All trials were recorded with a video camera focused in-line with the laser. This provides simultaneous data of the observational occurrences of flame and the measured emissions (attenuation).

Two conditions were examined with the wood blocks. In the first, a single block was placed on a flame limiter made of mesh with circular holes of 4 mm diameter separated by 2 mm, to prevent direct contact of the natural gas flame with the wood so the block was being heated but not allowed flaming combustion. This simulated the portion of the fire when wood is releasing some volatiles but unable to get the heat needed to transition to flaming combustion. In the second condition, a single block was held by a clamp with a flame surrounding it, revealing the full burn profile of the wood.

For the wood block trials, the optical path length (L) was considered to be the width of the wood block, namely 20 mm. In general, this leads to an overestimation of the path length. Time-averaged samples were taken every 15 seconds for the flame limiting trials and every 5 seconds for the open flame trials, allowing a visualization of the trends while averaging the fluctuations created by turbulence and an extremely variable flame.

4. Berkeley-Darfur Stove trials

To compare the basic burn configurations from the wood block with a real world condition, emissions from the Berkeley-Darfur Stove (BDS), an improved cooking stove, were also examined. The BDS is a wood-burning cookstove developed at Lawrence Berkeley National Laboratory (LBNL) for internally displaced persons in Darfur, Sudan. It is a proven fuel-efficient, natural-convection stove [9, 10]. Wood is combusted on a cast iron grate within a metal firebox to promote proper air flow through the combustion chamber and reduce heat losses to the environment.

4.a Experimental setup & Protocol

Five pieces of 20 mm × 20 mm × 150 mm Douglas fir were used as fuel. For each trial, the wood was stacked in a slightly askew pyramid (Fig. 2) such that the natural gas flame would ignite the middle of the stack. The bottom two pieces of wood were laid in a v-shape with the back ends touching and the front ends approximately 40 mm apart. The second layer was also v-shaped, approximately 10 mm apart in the front. The top stick was laid diagonally across with its front and back corners aligned with the centerline of the pieces directly below. The wood was ignited using a natural gas flame for 3 minutes; if the wood did not ignite in the first 3 minutes, 30 extra seconds of natural gas ignition were added to the test.

Figure 2: Wood configuration in BDS trials.

The wood was allowed to burn untended; no sticks were moved or turned and the fire was not fed. Data was recorded from the end of the natural gas ignition until no visible flame remained in the firebox.

Three holes, each of diameter 6.35mm, were drilled in the stove body wall and the fire box, perpendicular to the firebox opening, to allow the laser beam to pass through the stove with minimal light pollution from the flame reaching the photodiodes. The beam was aligned to the center of the firebox and approximately 10 mm above the top wood stick in the pyramid. For some trials, a camera viewed the burning wood pile from the firebox opening (perpendicular to the laser) to obtain an average flame width; other trials viewed the flame through a hole cut directly above the hole for the laser to observe when the laser was traveling through a flaming region.

For the BDS case, the path length was known to be no larger than the inner diameter of the firebox (190 mm) so that was chosen as the optical path length. It is important to note that in the majority of instances the path length is much smaller than the firebox, so the calculated soot volume fractions are potentially a significant underestimation. Time-averaged measurements were taken every 30 seconds.

Results

Trials revealed several trends in the wood combustion profile for a single block of wood that could be easily compared to the combustion in the BDS. Data from a few trials are shown in Figs. 3 - 6 to show examples of these trends.

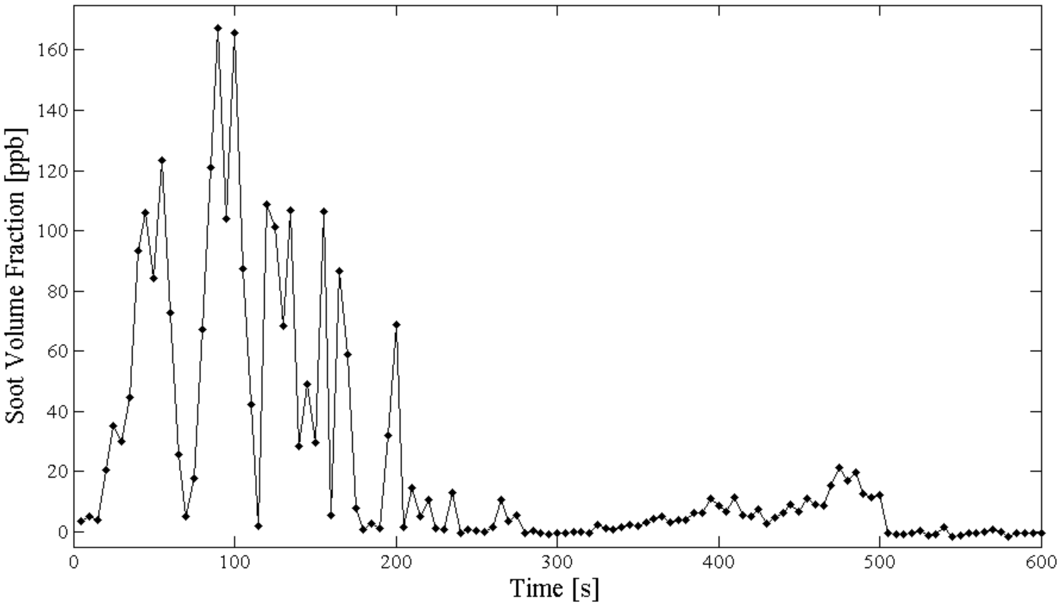

Figure 3: Typical results of the soot volume fraction from laser extinction measurements of a 20 mm × 20 mm Douglas fir wood block during the entire burn cycle.

From the observational videos of the case presented in Fig. 3, it is determined that charring of the wood begins almost immediately as the volatiles are released. From 0 – 180 seconds, the emissions measurements are sporadic. At this stage of combustion, values are higher and more variable while the wood is heating and releasing volatiles with lots of visible smoke, than values at a time greater than 200 seconds, when the wood is fully ignited. Once the exterior of the wood block has caught fire (at approximately 200 seconds), the emissions measurements drop dramatically. Only when the wood block is fully burning from the interior of the block (starting at approximately 330 seconds) is there any variation in the opacity. However, there is no visible smoke during this time, indicating these values relate solely to the release of soot. The ember fully extinguishes with a puff of smoke at around 480 seconds.

Fig. 4 shows the results from the laser extinction measurements for a typical BDS trial. Clear trends between the BDS trials and the wood block trials are evident. In Fig. 3, the fuel is allowed to fully flame and combust. When compared to Fig. 4, this indicates that during the BDS trial, the top stick is fully flaming and combusting in similar peaks. There is more variation as multiple sticks are at different stages of combustion at the same time, but the general trend is evident and provides an indication of the application of scale. That is, the results of a “simple” cube of solid fuel can be extrapolated with some confidence to more complex configurations of batch-fed solid fuel combustion.

Observational data indicates the presence of smoke for the first 400 seconds. After this stage, the exterior of the top stick fully ignites along with the other sticks, greatly decreasing the laser light attenuation. At approximately 800 seconds, the fire burns the entire stick prior to burning out. These trends are very similar to those found for the wood block.

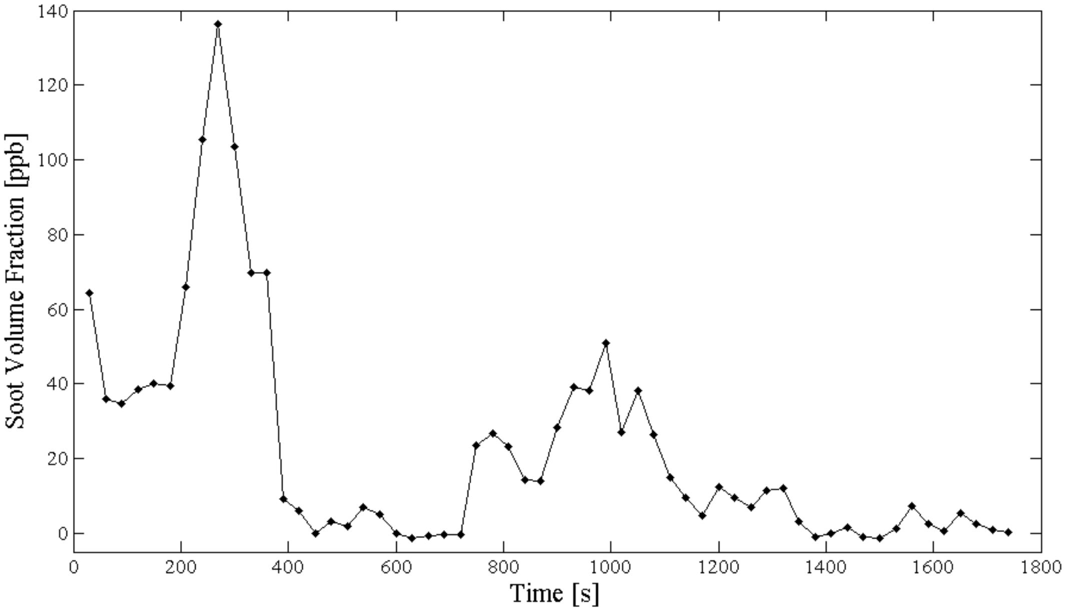

Figure 4: Typical results for a BDS trial throughout the entire burn cycle. Likely, the top stick is releasing its surface volatiles in the first 400 seconds and fully combusts those volatiles (400 – 700 seconds), providing enough heat to release and combust the entire stick in the remainder of the trial.

From an emissions reduction standpoint, it is evident even from these preliminary results that fully flaming combustion is the key mode for reduced emissions. Stoves should be designed to reduce the ignition time and the duration of smoldering, incomplete combustion, which produce much smoke and pollutants.

To further examine the precursor to the ignition stage, a 20 mm × 20 mm wood block was heated above a flame limiter. The results, combined with visual analysis, show very little opacity, little charring, and only minor peaks in the data. Example results are shown in Fig. 5. The results of extinction measurements with visual analysis indicate the wood block is releasing volatiles slowly without fully smoking.

The results in Fig. 5 help describe some unusual results obtained during the BDS trials. An example of these atypical BDS results is shown in Fig. 6. Although the same protocol was followed for both BDS trials shown in Figs. 4 and 6, due to the variable nature of wood combustion, the results are quite different. However, the results shown in Fig. 6 are similar to those shown in Fig. 5; the attenuation is small, but emissions are measureable. The peaks between 1000 – 1600 seconds in Fig. 6 are likely owing to the initiation of combustion of other sticks in the wood pile.

The similarity between Figs. 5 and 6 suggests that in some BDS trials, the top stick is never releasing smoke in view of the laser. However, as all wood piles were burned to completion for each trial, the top stick must be burning outside of the path width of the laser, which can happen if the wood pile collapses before the top stick is fully ignited. This indicates a future fundamental direction to explore in full stove testing – a multidimensional laser system to capture the 3D burning profile of the wood.

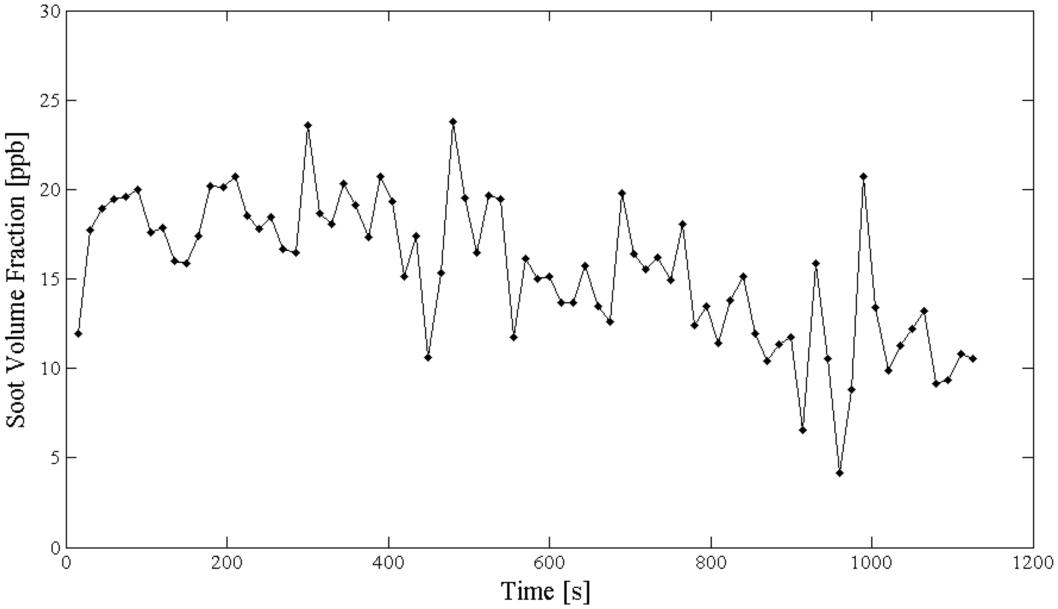

Figure 5: Example wood block trial where the wood block is sitting on a mesh flame limiter. Even though a continuous natural gas flame is below the flame limiter, the wood block is merely heated, charring slightly but never fully catching on fire.

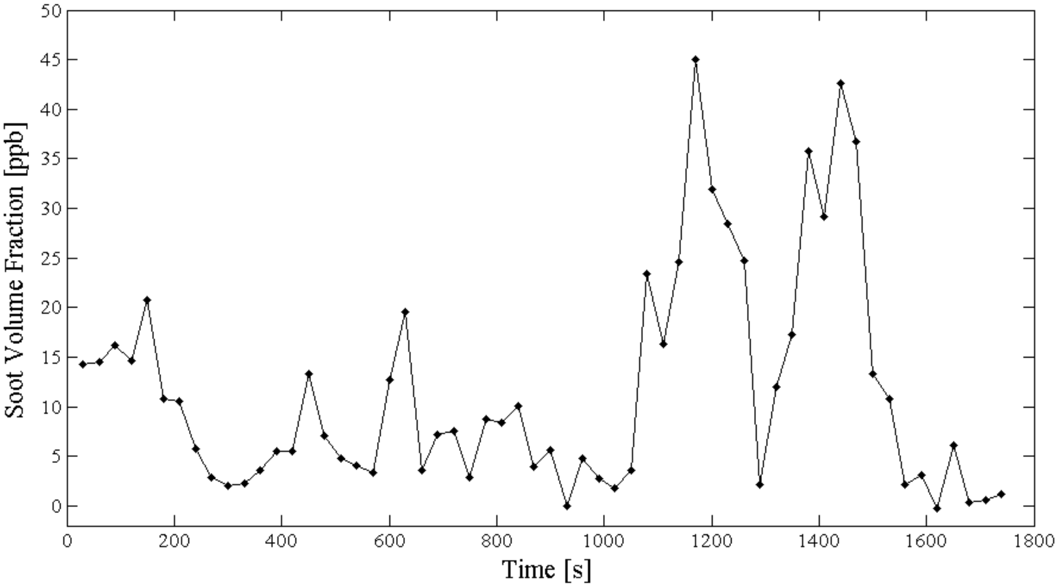

Figure 6: BDS trial where the top stick never fully ignited in view of the laser. Note that while emissions are being recorded, the peaks are not as large as those of fully flaming combustion sources indicating the release of fewer particulates in view of the laser.

6. Future Work

Laser diagnostic tests could provide valuable information to the cookstove community, but there is a long way to go before comprehensive data is obtained. A line-of-sight measurement system often misses valuable information about the wood if the flame travels away from the laser beam. Averaged measurements can be misleading due to the turbulent and sporadic nature of the flames and erroneous readings could be due to water vapor, etc. Future work will continue to study the effects of cookstove design modifications on wood block combustion to solidify the knowledge-base and explore the use of planar or multidimensional laser systems, such as those presented by Kalt *et al.* [11] or Medwell *et al.* [12]. Full scale testing on an improved stove is still a long way off, but valuable information can be gathered from the simple system of a small wood block.

7. Conclusions

Laser extinction measurements and visual analysis have been conducted on the combustion of burning wood in isolation and in a BDS. Results indicate that emissions are highest during ignition and during the final stages of combustion. That is, pollutant emissions are quite low when the fuel is fully ignited and fully burning. The ignition section of a burn is the smokiest, followed by the extinction of the flame. Modifications to reduce the ignition and extinction portions of burns would be helpful in reducing the smoke output of stoves. Additionally, trends in results from tests of single pieces of wood correspond to findings in the BDS with piles of wood.

Acknowledgements

Funding for this research was generously supported by a grant through the EAPSI program sponsored by the National Science Foundation and the Australian Academy of Science. The authors are grateful for the support from the Centre for Energy Technology (CET) and the University of Adelaide. The Australian Research Council (ARC) is acknowledged for equipment funding.

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