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Soot Reduction in Cookstoves due to Turbulent Mixing

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Abstract

Emissions from solid-fuel cookstoves, used by almost three billion people worldwide, create major issues for both human health and the environment. These emissions cause an estimated 4.3 million premature deaths annually and significantly contribute to environmental issues such as global climate change. One of the harmful emissions is soot and a promising option for reducing soot emissions from cookstoves is injecting air into the combustion chamber to increase turbulent mixing. Typically aerosol measurement systems are used to explore the effects of such modifications. However, these systems collect data relatively far away from the source, which makes it difficult to explore how the design modifications affect the actual flames. In this study, soot produced by a proxy-cookstove burner was measured in-situ using luminescence to explore the effects of different air injection modifications. The soot reduction trends were compared between different air injection angles and different air injection flow rates. Black carbon aerosol measurements were collected to compare with the values for in-situ soot and also to gain a quantitative value of black carbon produced in each case. It was found that overall trends appear to be consistent between the two measurement systems with all air injection modifications reducing black carbon over the baseline flame case and higher airflows proving to be more beneficial for soot reduction. Despite major differences in the amount of black carbon emitted from the flames recorded by the aerosol system, the luminosity intensity is similar for all cases, suggesting a significant increase in the soot oxidation with forced air flow. This indicates that the halo air injection systems are performing as desired, inducing turbulent mixing to reduce soot emissions.

Keywords: Cookstove, Luminescence, Soot, Black Carbon, Aethalometer

1. Introduction

Worldwide, nearly three billion people cook using solid fuels such as biomass and emissions from these fires lead to enormous health and environmental issues [1]. Smoke from biomass stoves has been found to be the largest environmental threat to health in the world, prematurely killing an estimated 4.3 million people every year [1, 2]. The burning of residential solid fuels also significantly contributes to outdoor air pollution and climate change, providing an estimated 25% of global black carbon emissions [3]. Due to these undesirable side effects, there is considerable interest in reducing soot emissions from biomass stoves [4].

One promising technique for soot reduction is injecting air into the combustion chamber of the stove to promote turbulent mixing. Mixing is a crucial component in soot reduction for non-premixed flames because a large fuel-rich zone exists where particulates are less likely to be exposed to oxidizers. Increased mixing breaks up this large fuel-rich zone into smaller pockets, raising the likelihood that soot particles will be exposed to air and thus oxidized prior to emission.

When evaluating cookstove performance, it is common practice to use an aerosol-based emissions measurement system, sampling far downstream from the stove in a duct which captures the emissions [5-7]. Aerosol emission measurements are useful when evaluating stove performance, but are not as informative about what is occurring in the flame zone itself because impacts to the flame must be hypothesized from measurements taken far downstream. Nonintrusive, in-situ measurements, like luminescence, provide a better view of how design modifications, such as air injection, are affecting the combustion in a stove.

The aim of this paper is to evaluate the impacts of air injection modifications on soot within a cookstove. The performance is assessed using a combination of both in-situ luminescence and ex-situ aerosol measurements. This systematic study of applying different injection angles and airflow rates to deduce promising modifications will guide future exploration and provide a comparison between concentrations of in-situ soot and ex-situ soot emissions.

2. Experimental methodology

Glowing soot particles formed in the fuel-rich regions of the flame produce a yellow luminescence [8]. This luminescence can be observed and recorded using a light collection device, such as a camera or photodiode, thus providing an estimation of soot in the flame based on the amount of light output, or luminosity.

Luminescence was chosen for these experiments as it is an uncomplicated, adaptable, and nonintrusive method of measuring soot concentration in a flame. A limitation of luminescence is that it does not provide a quantitative concentration, only qualitative results. However, these qualitative results allow for straightforward comparisons between different air injection modifications and provide insight on the locations of soot reduction in the flames. Aerosol measurements, on the other hand, provide a

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quantitative measurement of emitted black carbon, but do not offer information on locations of soot reduction.

Comparing results from the two techniques emphasizes the difference between in-situ soot (soot within the flame) and soot emitted from the flame. While it is desirable to reduce the soot emitted from a fire, the presence of soot within the flame is not entirely unwelcome as it increases radiative heat transfer to a cooking pot. Luminescence only measures in-situ soot, so soot may still be oxidized prior to leaving the stove but this would not be captured in the luminosity. As aerosol techniques measure the soot emitted, comparing luminescence and aerosol measurements can provide an idea of the amount of soot being oxidized outside of the flame front by each modification.

2.1 Burner and Air Injection System

A gaseous burner was developed that mimicked the thermal power and particulate emissions of an improved wood-burning cookstove, the Berkeley-Darfur Stove [5, 6], for proof of concept. The approach of having a well-controlled gas burner as a proxy for a wood-burning cookstove was chosen as wood fires are too variable for future laser-based experiments. The burner, shown in Fig. 1, is a trident-like system consisting of three parallel stainless steel pipes (each 254 mm long with a 21 mm outer diameter) spaced 19 mm apart. Nine 3.76 mm holes were drilled in each pipe situated such that the multiple small flames could interact, similar to a wood fire. Liquefied petroleum gas (LPG) was combusted in non-premixed flames with the flow of fuel held constant by an Alicat mass flow controller.

A toroidal manifold mounted above the burner, referred to in this paper as a halo, was used as the air injection modification. Three different halos were explored in this study; each halo injected air downwards onto the flames but were differentiated by the angle of air injected relative to the burner.

- The “Straight” halo had holes that aimed air directly downward onto the flames.
- The “Angled” halo aimed air inwardly at a 30 degree angle.
- The “Swirled” halo had the inward 30 degree angle of the Angled halo, but also included a 30 degree tangential component to add a swirling effect.

Each halo had ten 2.4 mm holes equidistantly spaced around the halo. The halo was mounted 154 mm above the burner, centered over the holes in the burner tubes. Three volumetric airflow rates were used for the experiments (28.3, 35.4, and 42.5 standard L/min), along with a baseline case where no air was added.

3. Luminescence Experiments

Images of the flames under the different halo and airflow cases were taken using a digital SLR camera. Several exposure times, ISO settings, and aperture settings were assessed to achieve the highest signal

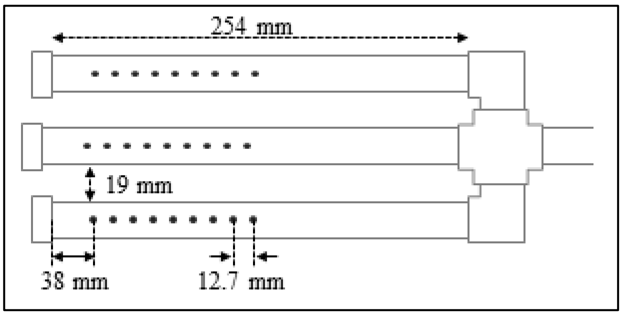

Figure 1: LPG burner designed as a proxy for an improved wood-burning cookstove. The parallel burner pipes are 21 mm diameter stainless steel with 3.76 mm diameter holes. The fuel enters the burner from the right of the image.

output with limited saturation for all halo and flow rate combinations. The signal-to-noise ratio of the images was found to be less than 2%. Total light emitted from the flames was also recorded with a photodiode. No filter was used, so the photodiode detected broadband flame emission. Background noise was removed from the total intensity before processing. The camera and photodiode were both mounted inline with the centre pipe of the burner.

3.1 Total Intensity

The average total luminosity intensity, shown in Fig. 2, was measured with the photodiode. All halo cases decreased intensity compared to the baseline, with the Straight halo leading to the largest reduction on average. As the measured intensity is taken as a proxy for the luminescing soot concentration in the flame, air injection through any halo appears to reduce soot production within the flame. Furthermore, in general an increase in air flow through the halo appears to suppress soot formation, consistent with the expected trend due to higher strain rate.

3.2 Intensity Radial Profiles

To visualise the effect of the different halos on the flames, mean profiles of the recorded intensity were developed from the luminescence images. Radial profiles of intensity (integrated over the total flame height) from the centreline of the burner outward are shown in Fig. 3.

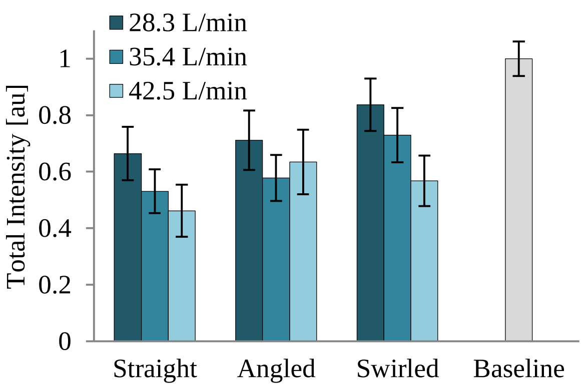

Figure 2: Total signal intensity of flames under different cases. All halos reduced soot compared to the baseline with the Straight halo providing the largest reductions on average. Error bars represent standard deviation (n > 1000).

Luminescence images for each halo are shown in Fig. 4. Each image is the average of approximately 1000 still images and represents a viewing area of 238 mm by 162 mm. These sample images are for the lowest halo airflow rate, 28.3 L/min.

The baseline case profile shown in Fig. 3 has two strong intensity peaks in the radial direction, one at the centreline and the other at approximately 40 mm. This corresponds to the flames from the centre pipe and one of the outer pipes of the burner. In the images, it is the same with three strong flames shown in Fig. 4A.

The Straight halo pushes these flames downward, theoretically increasing mixing so the soot is exposed to oxidizers. At low flow rates, like shown in Fig. 4B, flames still rise through the centre of the Straight halo, but as the flow increases, all flames are more equally mixed. This explains the strong soot reduction shown in Fig. 2 and why the soot decreased as airflow increased.

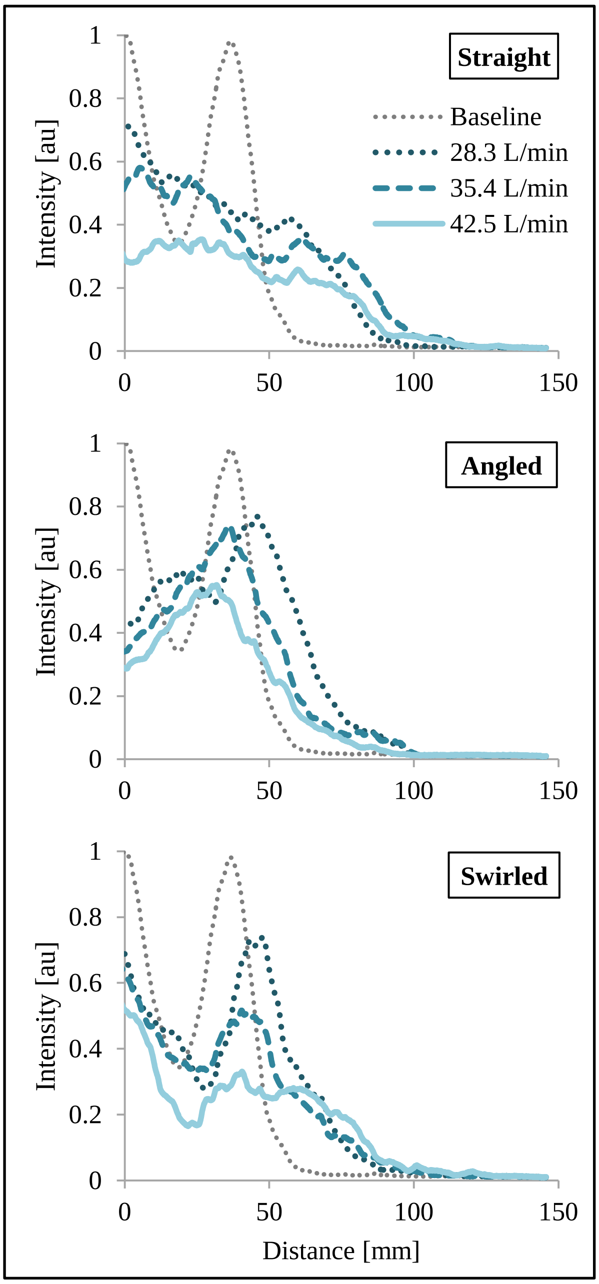

Figure 3: Mean radial profiles of signal intensity for each Halo: Straight (Top), Angled (Middle), Swirled (Bottom). The baseline case is shown on all three graphs for comparison.

The Angled halo primarily breaks up the fuel-rich zone in the centre flame where the air converges, leading to the reduced intensity seen in Fig. 4C and explaining the improved soot reductions over the baseline in Fig. 2. However, it allows the flame from the outer pipe to rise up the outer edge of the injected air (around 40-50 mm in the radial direction of the profile), which is likely why the Straight halo had larger reductions.

The Swirled halo profile has two interesting trends apparent. An almost constant peak is maintained along the centreline even with increased air flow. As this peak is not observed in the Angled halo case, it is most likely due to a swirl effect caused by the tangential component of the Swirled halo because the two halos are otherwise identical. Indeed, a swirling central vortex was visually observed during experiments. Similar to the Angled halo, the outer flame is present at low flow rates as the air injection does not greatly impact the flames near the burner, shown in Fig. 4D. However, as seen in the profile, if the flow rate increases, this outer flame is reduced almost to the level of the Straight halo as that soot is likely oxidized by air entrained by the central vortex.

4. Ex-situ Measurements

Black carbon aerosol measurements were taken using a rack-mounted aethalometer, Model AE22, manufactured by Magee Scientific. An aethalometer is an instrument that determines the mass concentration of black carbon by passing an aerosol sample through a filter and measuring the light absorption as carbon particles collect on the filter. The aerosol experiments were conducted with the burner and halo in an exhaust hood system which controlled and monitored airflow rates through the duct. Real time (1 Hz) measurements were taken by the aethalometer from the exhaust ducting, sampled approximately 2.5 m downstream of the burner.

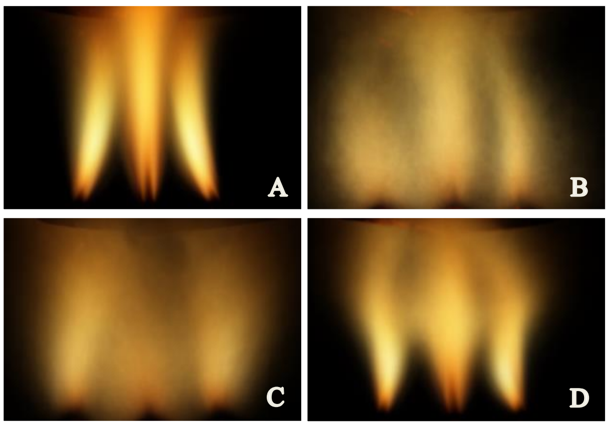

Figure 4: Averaged images of flames in each halo case: (A) Baseline, (B) Straight, (C) Angled, and (D) Swirled. Images represent a 238 mm by 162 mm viewing window and the lowest airflow rate is used in all halo images.

The ex-situ results shown in Fig. 5 follow similar trends to the in-situ results shown in Fig. 2: (1) all halo and air combinations reduce soot in comparison to the baseline; (2) the Straight halo performs best followed by the Angled and then the Swirled; and (3) as the flow rate of air increases, the soot decreases.

An important distinction is noted in the level of soot reduction measured between the baseline and halo cases; the difference between baseline and halos is far larger and more significant in the ex-situ results. This is likely due to the air injection modifications performing as desired – soot still forms within the flame, resulting in high luminosity, but the increased turbulent mixing from the air injection oxidizes soot prior to its emission.

5. Discussion

An important consideration is the effect of the air on the flame strain rate. If air strains the flame too much this could lead to local extinction. It could be expected as the airflow rates increase, the probability of quenching occurring also increases, and this could lead to an increase in soot released from the flame. A further sign of flame quenching is an increase in carbon monoxide (CO) emissions [9]. To help identify quenching, a California Analytical Instruments NDIR gas analyzer measured CO emissions in the same aerosol system as the aethalometer. The baseline case emits three times the amount of CO as any of the halo cases so any quenching effects appear to be small in this system. However when optimizing an airflow rate for these modifications, closer consideration will need to be taken to evaluate and mitigate quenching effects.

It is also important to note that the burner used in this work is a proof of concept; the real cookstove is a very complex system with many important aspects besides soot emissions, such as gaseous emissions, fuel consumption, thermal efficiency, cultural relevance, and ease of implementation. In a real cookstove, for example, there is a cylindrical combustion chamber which will provide containment for the flames and injected air and promote mixing, especially for the Swirled halo Future work is therefore necessary to evaluate effects of the halos in the real stove.

6. Conclusions

The soot emitted from the global use of cookstoves has large adverse impacts on health and the environment; forced air modifications are proposed as a possible technique for decreasing the amount of soot emitted from cookstoves. In this paper, the potential for soot reduction using air injection was explored using both luminescence and aerosol systems. The comparison of in-situ and ex-situ measurements of soot reductions due to air injection modifications has shown similar trends: all air injection cases evaluated reduced soot compared to the baseline and generally as the air flow increased, the soot concentration decreased. However, the difference in magnitude between the in-situ and ex-situ reductions indicates that the halos do not affect soot formation in the flame, so high luminosity is measured, but the forced air is successful at promoting oxidation of the soot prior to its emissions and measurement ex-situ.

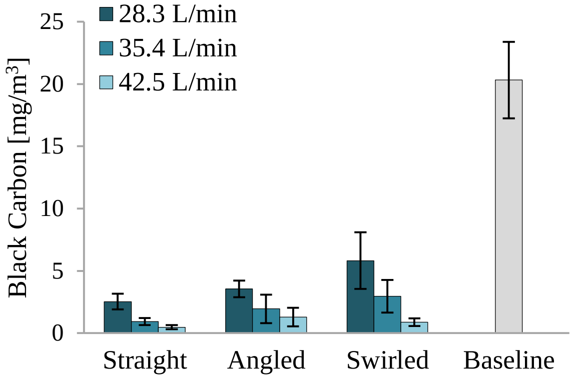

Figure 5: Ex-situ average black carbon emissions. Similar to the in-situ results, all halos reduced soot compared to the baseline with the Straight halo providing the largest reductions on average. Error bars represent standard deviation (n > 1000).

7. Acknowledgments

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